# AN EXPERIMENTAL STUDY OF THE EFFECT OF WIND-INDUCED DRIFT ON THE ROLL RESPONSE OF A HULL IN BEAM SEAS

William W. Rogalski

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by

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## ABSTRACT

Model tests were run in beam seas, both regular and irregular, with transverse drift velocities of 0 and 2.03 knots (full scale) to determine if drifting has any effect on the roll response of a ship. Wave heights at three points around the model were measured and a comparison between the vertical midships bending moment in beam and head seas was made. The regular sea results are presented as response amplitude operators, while the random sea results are given in spectral density form.

The roll response in the region of roll resonance for the drifting case shows considerable attenuation, and a total reduction in significant roll was noticed in the 30 knot sea state test. It is believed that this roll attenuation is primarily a result of increased apparent damping. Further tests, especially in the higher sea states, are necessary because the narrowness of the towing tank used for this series of tests may have compromised the results.


Thesis Supervisor: Martin A. Abkowitz

Title: Professor of Naval Architecture

## ACNOWLEDGEMENTS

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The typists, Mrs. Viola Liddell and Miss Alice Habberton, also deserve a note of thanks for giving up their time to help in finishing this paper by the deadline.

All model tests were run at the M.I.T. Ship Model Towing Tank. The computer analysis of the data was done at the Mechanical Engineering Computation Center at M.I.T. and at the M.I.T. Computation Center.

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# INTRODUCTION

Whenever a storm occurs at sea, the usual practice for ships caught in it is to turn their bows into the predominant wind and sea components and heave to or maintain a small amount of headway. In this condition a ship is in no great danger of rolling over, but there is a distinct possibility that she may break in half because of the excessive vertical bending moment generated in this condition. The question arises of what would happen if the ship were to drift with the wind and seas with her beam facing the weather, whether by accident (machinery breakdown) or on purpose? Would the seas necessarily roll the ship past her stability range, or because she was drifting would the roll be alleviated?

It is the purpose of this project to determine if there is any significant reduction in the roll response of a ship drifting beam to weather as a result of the wind when compared to the response of a ship with her beam to weather with a zero drift velocity. Also to be compared are the magnitudes of the vertical bending moments generated by head and beam seas. This is done to verify the prediction that the bending moment will be much less in beam seas.

The tests will be run in regular seas with both zero drift velocity and a drift velocity of 2.03 knots (full scale) to obtain response amplitude operators. Then the same two conditions (zero and 2.03 knot drift) will be run

in irregular seas. The sea states to be used are of the form of Pierson-Maskowitz sea states and consist of the following wind velocities: 20, 25 and 30 knots.

## MODEL PREPARATION

The hull used is a fibreglass shell model of the American Racer, a high speed cargo liner operated by United States Lines. The model is split in half at the midships section, and the two parts are joined by a flexure bar. This setup, along with suitable instrumentation, permits the measurement of vertical bending moments.

The primary modification to the model for this series of tests consisted of fitting a roll bearing to the hull. An ordinary pitch bearing was used except that the entire bearing was mounted so that its axis was rotated 90° from its usual position. It was also desired to superimpose the axis of the pitch bearing on the roll axis of the model to eliminate as much as practicable any outside forces on the hull as it rolled. To accomplish this the roll bearing axis was mounted on the longitudinal centerline of the ship at the same level as the waterline. For small angles of roll (<10°) the roll axis of the ship would be located there, and it was assumed that for this experiment that location for the bearing would give satisfactory results.

Since roll can be affected by pitching motions, a result of port and starboard asymmetry when the ship is at some particular roll angle, it was decided to include pitch as one of the degrees of freedom along with roll and heave. Additionally, if the model was not free to pitch,

spurious bending moment readings would result since the hull is asymmetric fore and aft. Also the dynamic component of the bending moment could not be measured if that were the case.

To eliminate as much as possible the above problems a pitch bearing was mounted on the top of the roll bearing with the heave rod fitting into the socket of the pitch bearing. Although the pitch bearing axis was located at deck level, it was felt that this location shouldn't affect the roll and bending moment data anywhere nearly as much as if the pitch bearing was eliminated.

Since a pitch bearing was fitted,it was necessary to scale the longitudinal moment of inertia of the model so that the pitch period is scaled correctly. The procedure followed to achieve this is a standard one and can be found in Reference 1.

Because the primary object of the experiment was to measure the roll, it was imperative that the roll period be scaled. This was done by first determining what the roll period of the model should be (see Appendix "D"). Then the model was attached to the towing carriage, and given an impulse excitation to start it rolling. The damped roll period was measured and compared to the approximate theoretical period. Ballast was then shifted until the actual roll period matched the calculated one to an acceptable

degree. Because weights were moved to correct the roll period, the pitch period was checked and found to be in error. An iterative process of shifting ballast and re-checking the pitch and roll periods then shifting ballast again, etc., followed until both matched the required periods, within experimental limitations.

Scaling the roll period eliminated the possibility of having a deckhouse to keep the instruments dry. The weight of the deckhouse so high in the model would have increased the roll period to an unacceptable value so a plastic garbage bag was used to seal off the instrument area from the water. The bag was also made necessary because any deck-house high enough to keep water out of the model would have hit the heave rod when any appreciable roll angle was encountered. The bag was flexible and light enough so that it did not affect the motion of the model in any significant manner.

As mentioned earlier, the model was segmented amidships and fitted with a bending moment dynamometer. The details of this setup can be found in Reference 2, but a few points are worth mentioning.

In Reference 2 Sellars and Goda mention that the axis of the pitch bearing should be at the same height as the flexure bar to eliminate any bending moment arising from the towing force. In this series of tests that problem is

not present because towing the model sideways will not produce any vertical bending moment, and even when the model is being towed into head seas later in the testing, its speed is too low to create any problems.

Also the bending moment dynamometer assembly being so heavy severely restricted the ballasting of the model. It made ballasting to satisfy the pitch and roll period requirements extremely difficult, and hampered the calibration of the bending moment transducer (see page 34 ). Unfortunately such a heavy assembly is necessary so that the bending moment transducers are mounted on as rigid a foundation as possible (Ref. 2).

## MODEL AND TANK INSTRUMENTATION

Roll angle was measured by a rotary variable differential transformer attached to the roll bearing. A Sanborn carrier preamplifier provided an excitation voltage for the transformer and amplified or attenuated the return signal from the transducer before feeding it to the six-channel chart recorder and the magnetic tape recorder. Since the anticipated roll angles were to be much greater than the usual pitch angles encountered,, it was found that the signal from the roll transducer was so great that a Sanborn Linearsyn 595DT-025BM attenuation circuit had to be inserted between the transducer and the carrier preamplifier to achieve the desired input amplitude to the recording instruments.

Heave measurements were made by a linear variable differential transformer connected to the heave rod assembly. Excitation, signal amplification, and signal recording were accomplished in the same manner as for the roll bearing, except that the additional attenuation circuit was not needed.

Parallel wire resistance wave probes were used to measure the wave height at three different points around the model (see Appendix C). Because the probe wire supports were streamlined and the resistance wires very thin,

the waves created by the moving probe and interference with the sea state were considered very small and thus neglected. All three probes used circuitry identical to that of the heave bearing.

Two methods for measuring the vertical midships bending moment were available in the model used - a linear variable differential transformer mounted on the end of a lever arm, and strain gages bonded to the flexure bar connecting the two parts of the hull. Measurements using both transducers were desired as a check on the instruments, but the strain gages were inoperative. No method of excitation and amplification tried would produce an output even under extreme bending conditions. The strain gages probably became detached from the flexure bar or some wires may have parted or shorted out, and since the strain gage assembly was sealed by the manufacturer, no attempt was made to repair them. The linear differential transducer proved to be successful when connected to a carrier preamplifier, except that it did not produce as large an output as was desired.

## EXPERIMENTAL PROCEDURE

The first part of the experiment entailed the calibration of all the instruments. The roll bearing was first zeroed and calibrated using a protractor designed for that purpose. Then the bearing was put in the model, and with the model attached to the heave rod, the zero point and calibration were checked by rolling the model to known angles by hand with the aid of another special protractor. In all cases the calibration done in the model and the calibration done with the protractor agreed. It was thought that the wiring from the carriage to the instrumentation room would affect the reading, but it did not.

Before the wave probe calibration began, all the probe wires were thoroughly cleaned with an aerosol degreasing compound. Then they were clamped to the carriage at their respective locations and calibrated by loosening the clamps and moving the entire probe up and down in the water.

Calibration of the heave rod followed. In this case a zero point was determined by connecting the heave rod to the model floating in calm water; then a zero point was obtained by moving the linear transformer casing along the transformer core until no signal came out of the transducer. The heave rod was calibrated the same way - by

moving the transformer casing instead of the core which was attached to the model connecting rod assembly.

The bending moment dynamometer calibration proved to be the most involved calibration procedure. To calibrate it, the model was placed in the water with two weights placed on the roll bearing mounting plate. These two weights represented the weight of the heave rod, connecting bar and bearing assembly in the simulated test condition. The instruments were zeroed in the test condition and then known bending moments were applied by moving the weights a certain known distance from their position on the mounting plate. This enabled a calibration of the bending moment differential transformer. For an illustration of this technique see page 34.

The calibration of all instruments was checked about half-way through the testing period and again at the end to see if any change had occurred. The wave probes were also cleaned again at the half-way point.

Waves both regular and irregular were generated by a paddle type wavemaker at one end of the tank. Command signals for the regular seas were generated by a low-frequency sine wave oscillator while the sea state commands came from a magnetic tape. The command signals coming from the tape recorder had to be fed into a Krohn-Hite band-pass filter before going to the wavemaker because "spikes" in

the tape would cause the paddle to slam in any other case.

The regular seas tests were run in waves with an $h/\lambda$* equal to 1/100 and wave lengths ranging from 6.0 to 17.0 feet. Because the tank is only 48" deep, shallow water effects were taken into account when setting the input frequency for the longer wave lengths. To achieve the proper wave height the wavemaker was run without the model in the tank and the wavemaker potentiometer settings noted. For the actual tests with the model in the tank, the potentiometer was set at the various predetermined values for the different $\lambda$'s. The potentiometer settings were checked before each set of runs, if the sets were run of different days, to insure that the wave heights were always correct.

The two model speeds used in these tests were 0 and 0.207 knots (2.03 knots full scale). Ideally for each sea state a different drift speed should have been used since wind-induced drift was being simulated, but the lowest finite speed of the towing carriage was 0.207 knots. This speed might have been a little too fast for the less severe sea states, but it approximated a drift speed closely enough to make the tests valid.

For the actual test the model was positioned about half-way down the tank for the zero velocity case and the

*h = wave height, $\lambda$ = wave length

wavemaker was run until the model and wave responses reached steady state and about 30 seconds of valid data was recorded on the chart paper. The same technique was followed for the drifting case. Between all test runs enough time was allowed to enable the surface of the tank to become completely calm.

The model was also tested in irregular seas with the Pierson-Moskowitz 20, 25 and 30 knot sea states being used (Reference 3). The sea states were produced by a process of filtering a white noise spectrum to obtain the desired Pierson-Moskowitz spectra (Reference 4), and the resulting wave record was put on magnetic tape. The proper wavemaker potentiometer settings for the sea states were obtained in the same manner as they were for regular seas. In this case a sine wave of a height equal to that of the $H^{1/3}$'s of the sea state under consideration was put before each sea state record on the magnetic tape. This sine wave was played into the tank for each irregular sea and its height adjusted until it was scaled properly. The same precautions were taken with the irregular sea potentiometer settings as with the regular seas.

The irregular sea runs were done in a manner similar to the regular sea runs. For the zero velocity condition, the model was again positioned about one-half the way down the

tank with data being taken for two-minute intervals separated by enough time to let the tank calm down. It was hoped that this technique would prevent the build-up of transverse and reflected waves in the tank.

The test program can be found in Appendix E. An attempt was made to test the model in 35 knot beam seas since the higher sea states were of primary concern in this project. When tried, the 35 knot sea state jarred the model and carriage so much that the heave rods were jarred loose from their supports. It was decided to terminate the experiment before any serious damage was done to the heave rod assembly. The reason for the separate run for heave and bending moment measurements was that there were only four carrier preamplifiers available, and they were all being used to measure wave heights and roll.

The data on magnetic tape was digitized and put on computer cards using the M.I.T. Mechanical Engineering Department's analog-to-digital conversion routine and the EAI 680 and IBM 1130 computers. The digitizing rate was selected as 10 cps model scale or 1.02 cps full scale to insure that all significant response frequencies were included. The resulting data was spectrally analyzed (Reference 5) at the M.I.T. computation facility and presented in graphical form.

# RESULTS AND DISCUSSION OF RESULTS

The results of the experiment can be found in Appendices F and G. All values in the table and plots imply peak-to-peak motions, i.e., wave heights, and roll from one side to the other.

Looking at the response amplitude operator curves for roll, it is evident that there is significant reduction in the roll response in the region around the natural period of roll ($\omega$ = 0.427 rad./sec.) for the drifting case. The reduction of the roll response in this manner was the hoped for result. There are two unusual aspects of these response operators though - the rise at short wavelengths and the dip below one on the right side of the resonant peak. Since roll is rather highly tuned to its natural frequency, it would be expected that the curve would fall rapidly to zero in the shorter wave region, and fall smoothly to one without dropping below that value for the longer waves. One possible explanation is that the heave and pitch motions coupled with the roll tend to modify the expected second order response curve into the present shape. The slight hump in the region of $\lambda$ = 6 feet could be a result of the pitching and heaving effect on roll. When the ship has a roll angle it no longer has port and starboard symmetry, and the pitching and heaving motions could

excite roll. This effect could be very influential in waves of the same frequency as the either natural heave or pitch frequency since the model has its shorter dimension parallel to the motion of the waves. For this particular model the natural heave response occurs around the 5 to 6 foot wave lengths, the location of the secondary roll peak. This coupled system could also be the cause of the dip below one in the region above resonance. These secondary effects were not as noticeable in the drifting case, and this along with the fact that the resonance peak flattened out would seem to indicate that additional damping was present in this situation.

The irregular seas data produced some interesting results also. First of all it was found that the significant heights of the waves measured in the tank especially at the bow and wake probe positions were significantly greater than the significant heights of the ideal Pierson-Moskowitz spectra. This appears to be a result of waves reflecting back and forth between the model and the wave-maker paddle. Tank tests are usually not bothered with this problem, but in this series of tests the model mounted across the tank could have acted as a wave reflector and filter and produced the effects. The increase in significant height appears to be too great to be caused by

the heave and roll damping waves. In addition, it was observed during one of the tests in regular seas, that when the wavemaker was inadvertently left on for a period of about three minutes, the roll angle started to rise above its steady state value, a possible indicator of the build-up of reflected waves.

As far as the reduction in roll is concerned, the 30 knot sea state runs were the only ones which supported the hypothesis. In all other cases the drifting roll effectively remained the same as the zero drift roll; however, in all the tests the wake and bow wave significant heights were reduced. Looking at all the wake wave spectra for the no drift and drift conditions, in all cases during the drifting mode the high frequency components of the wake spectra were reduced, in some instances quite drastically. A check of the group velocity of the high frequency waves ruled out the possibility that the model, since it was moving, reduced the reflected wave build-up. Its speed of advance was just too low to be of any consequence. Also it would be expected that the wake and eddies around and behind the moving hull would affect the higher frequency components of the input the most. It was noticed too, that the spectral peaks of all the wave spectra were reduced, but not by as much as the secondary high frequency peaks.

All the roll response spectra for the zero drift case showed a high peak at the natural period of roll (roll is finely tuned), but once the model was moving all these peaks were cut significantly verifying the flattening of the response amplitude operator curve. The secondary peak near heave resonance was present in the zero drift case as on the response operator, but in the 2.03 knot drift case the high frequency response increased, for the 20 and 25 knot sea states, opposite to the regular seas result. Of course much depends upon the shape of the input spectra and perhaps in these tests the wake probe alone was not enough to determine a valid input.

The only case that fit the hypothesis well was the 30 knot sea state test. The significant roll values showed a definite reduction, and the resonant component also decreased tremendously when the model drifted. This case fell out so well because the peak excitation for the 30 knot sea state was near the natural roll frequency.

The bending moment in beam seas showed a marked reduction in magnitude over the head seas condition. There were a few spikes in the beam seas data, but these appeared to be a result of waves slamming into the hull when rolled away from the seas and from the model being pushed and jerked around while fixed rigidly to the heave rods.

## CONCLUSIONS AND RECOMMENDATIONS

Based on the significant roll response reductions obtained in regular seas and in the 30 knot sea state around the region of roll resonance, it is believed that the drift does have some effect on roll. The exact reason for this is still not known and will not be known without further experimentation, but it seems to have to do primarily with some type of damping effect. When the model was being tested in regular seas no reduction in the excitation was noticed with the model drifting, yet at the same time there was a drastic drop in roll response at resonance. The way that the response operator for the drifting mode flattened out (the resonance peak, the heave-induced peak, and the dip at the longer wave lengths, all became less) seems to imply that the roll is being damped in some manner. The reduction in the resonance peaks in the roll spectra also seems to bear this out. There just does not appear to be enough of a reduction in the excitation to cause the response to drop so much. Perhaps the flow patterns around the hull are modified in a beneficial manner or the wake is affecting the roll damping wave train in a way so as to decrease roll. Of course, if the roll damping wave was affected, why wasn't the heave wave also affected?

The bending moment results were satisfactory. It was seen that the vertical bending moment in beam seas was quite a bit less than that in head seas.

If any future tests of this type are to be run, it will be necessary to conduct them in a much wider towing tank to eliminate the interference caused by the small space between the model and the tank, and the tank walls. Ideally, the tank should also be quite long and the model positioned as far from the wavemaker as possible to eliminate the effect of reflected waves. Short runs would also solve the reflected wave problem. It was felt that the validity of this experiment was partially compromised by all the odd wave effects up and down the tank and around the model, so something must be done to see if this is a valid complaint. Tests in higher sea states would also be desired. Since significant roll attenuation was first noticed in the 30 knot sea state, it would be interesting to see if this is continued into the more severe seas. After all, the purpose of the tests is to see how much a ship does roll in seas which could split it in half.

## REFERENCES

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2. Frank H. Sellars and Goda,Kunio,"The Experimental Measurement of Ship Model Bending Moments in Waves." M.I.T. N.A.M.E. Dept. Report 65-2 (Cambridge, Mass., 1965).

3. John P. Comstock, ed., *Principles of Naval Architecture*, (New York, 1967).

4. Martin A. Abkowitz, Vassilopoulas, L. A., and Sellars, F. H.,"Recent Developments in Seakeeping Research and Its Application to Design." S.N.A.M.E. (New York, 1966).

5. L. A. Vassilopoulos,"A Compendium of Results from the Theory of Random Processes for Application to Seakeeping"(Cambridge, Mass., 1965).

# APPENDIX A

## SHIP AND MODEL PRINCIPAL DIMENSIONS

Ship: *American Racer*

Scale Ratio: 96:1

| | Model | Ship |
|---|---|---|
| LOA | 5.56 ft. | 534.0 ft. |
| LBP | 5.28 ft. | 507.6 ft. |
| Beam | 0.781 ft. | 75.1 ft. |
| Depth | 0.443 ft. | 42.5 ft. |
| Draft | 0.281 ft. | 28.0 ft. |
| Displ. | 41.806 lbs. | 16,510 tons |
| $C_b$ | 0.578 | 0.578 |
| $C_{pl}$ | 0.588 | 0.588 |
| LCB | 0.064 ft. aft | 6.15 ft. aft |
| $K_y$ | 1.32 ft. | 0.25 LBP |

# APPENDIX B

## WEIGHT BREAKDOWN

| | |
|---|---|
| a) Hull including bending moment dynamometer .................... | 32.71 lbs. |
| b) Ballast ........................ | 4.43 lbs. |
| c) Decks .......................... | 0.55 lbs. |
| d) Pitch and roll bearings and mounting plates ............... | 1.06 lbs. |
| e) Heave rod ...................... | 3.00 lbs. |
| f) Connecting piece .............. | 0.48 lbs. |
| Total .................. | 42.23 lbs. |

# APPENDIX C

## ILLUSTRATIONS OF TEST SETUP

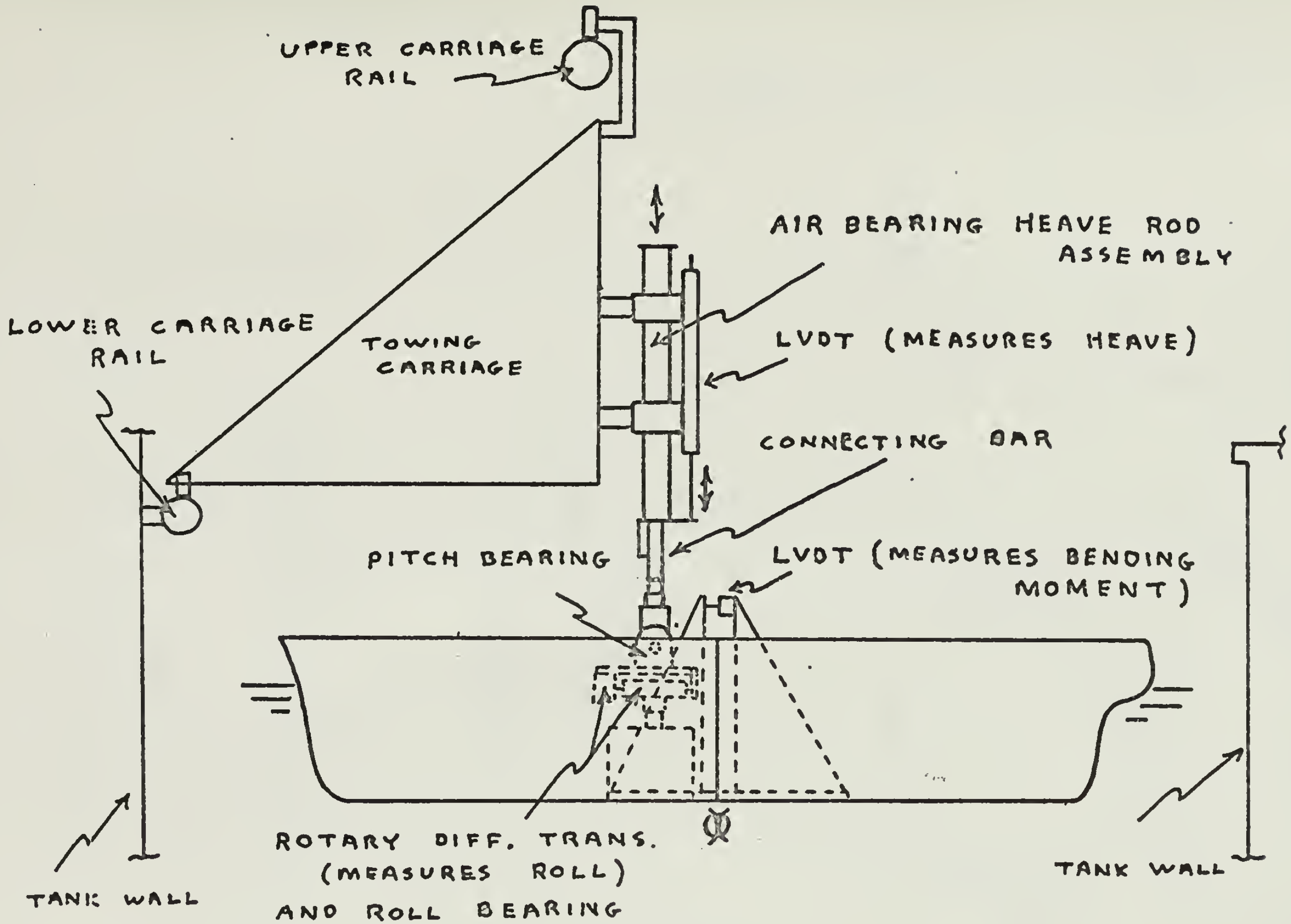



Fig. 1. Model Hookup to the Carriage;
View looking away from the wavemaker.

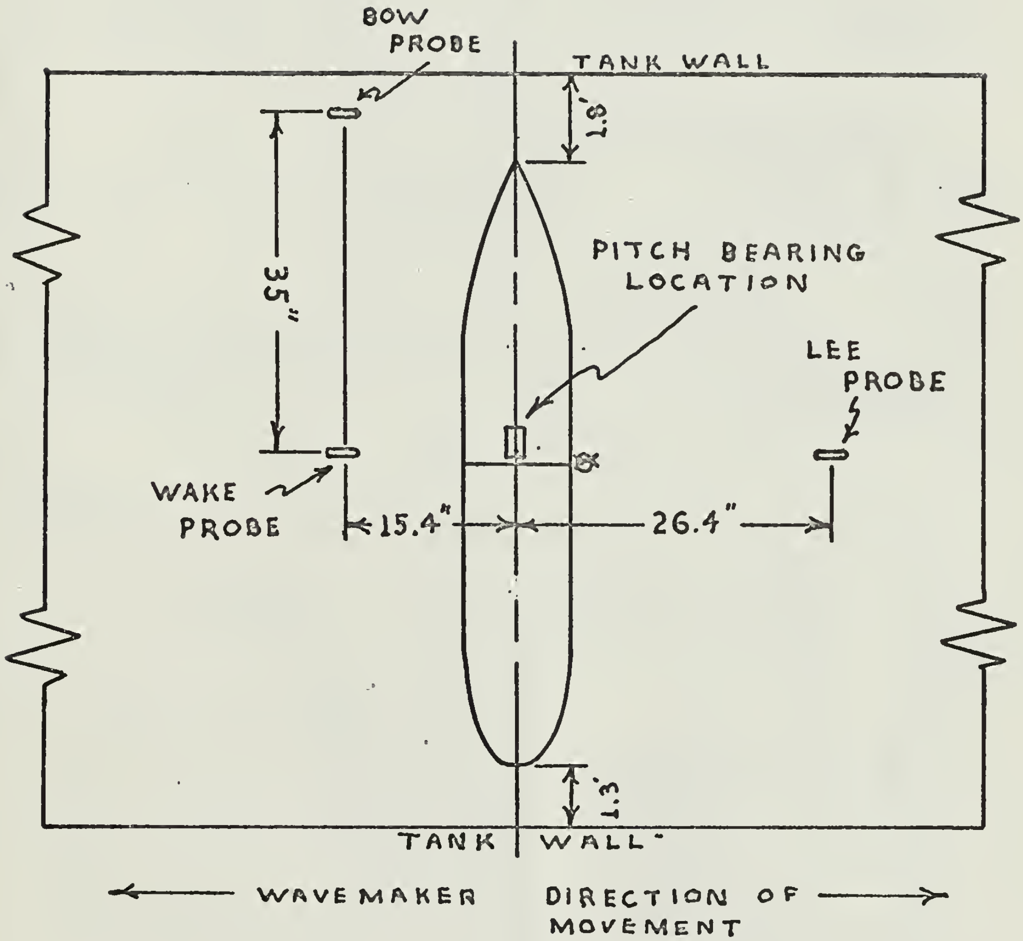



Fig. 2. Looking down on the model showing the location of the wave probes.

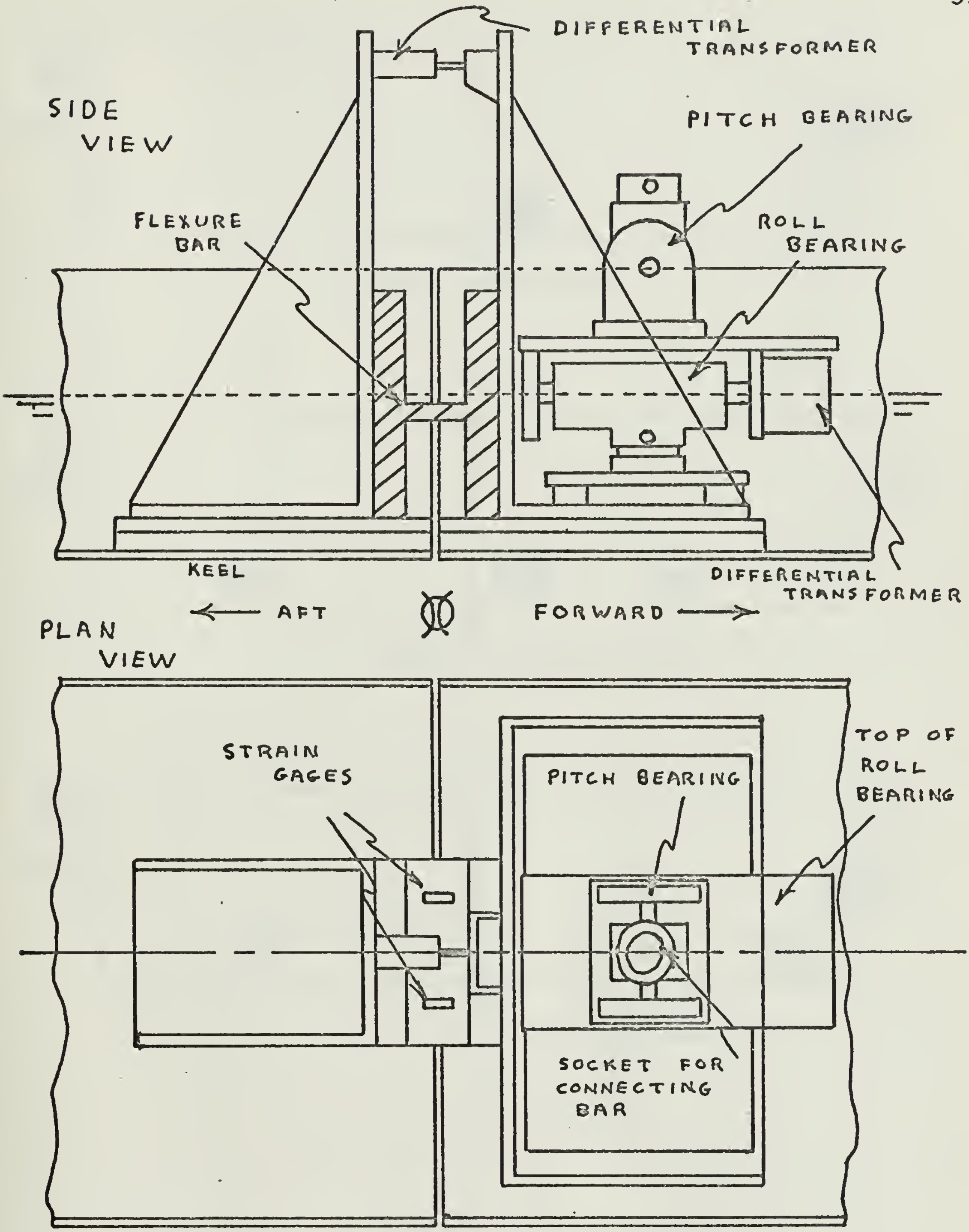



Fig. 3. Midships area of the model, illustrating the roll-pitch bearing assembly and bending moment dynamometer.

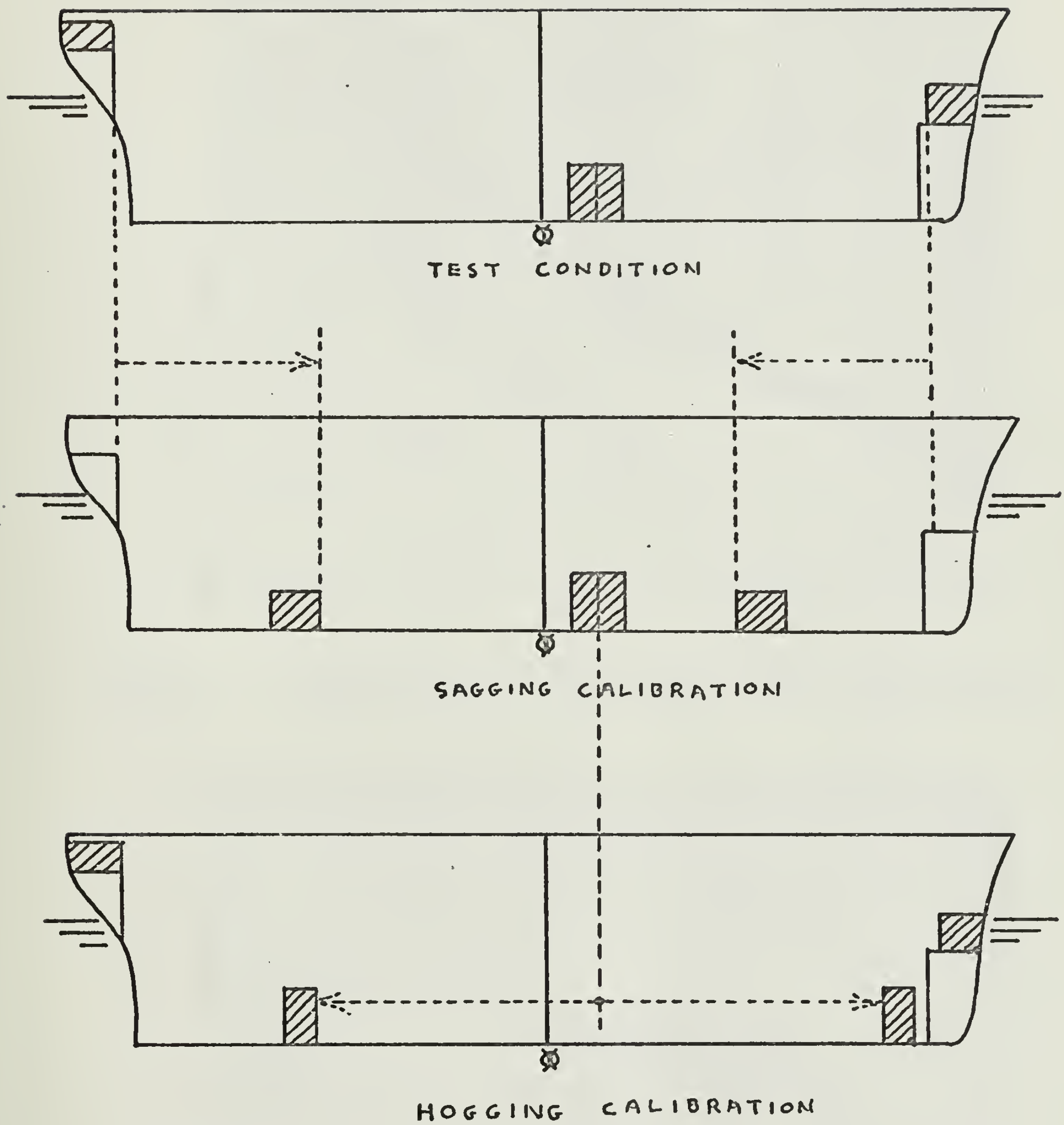



Fig. 4. Bending Moment Dynamometer calibration procedure.

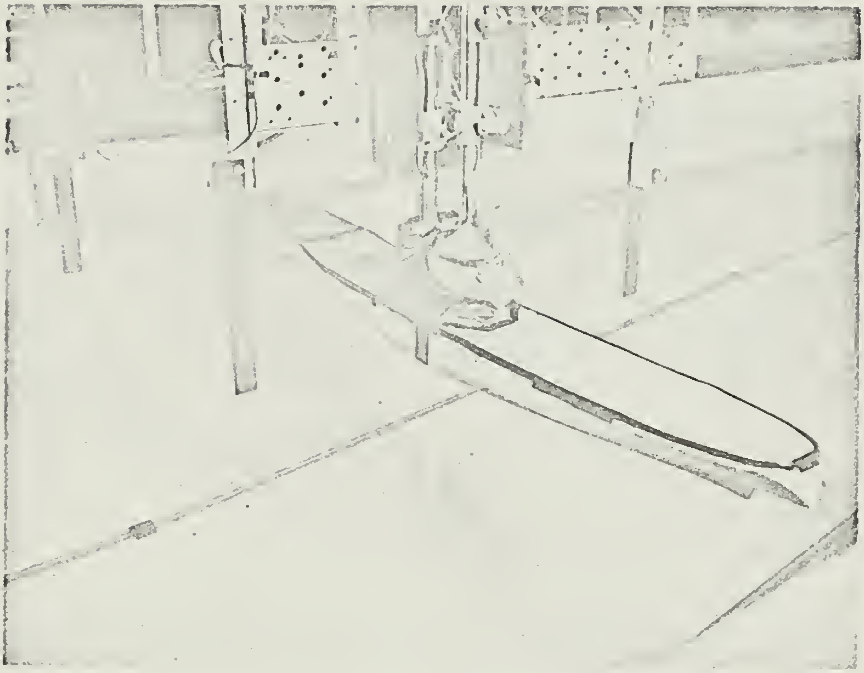


Fig. 5 Model set-up showing the three wave probes.

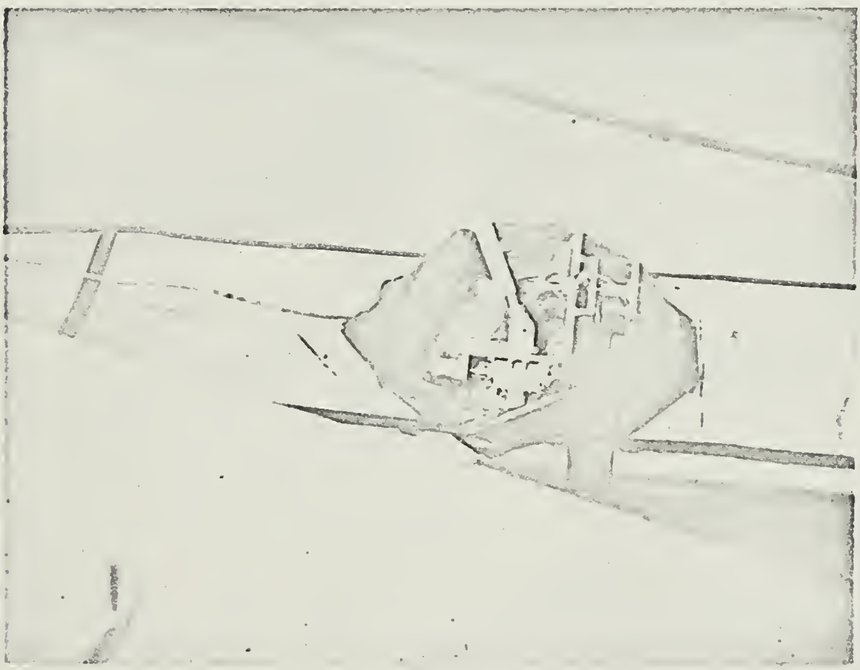


Fig. 6 Roll and pitch bearing assembly.

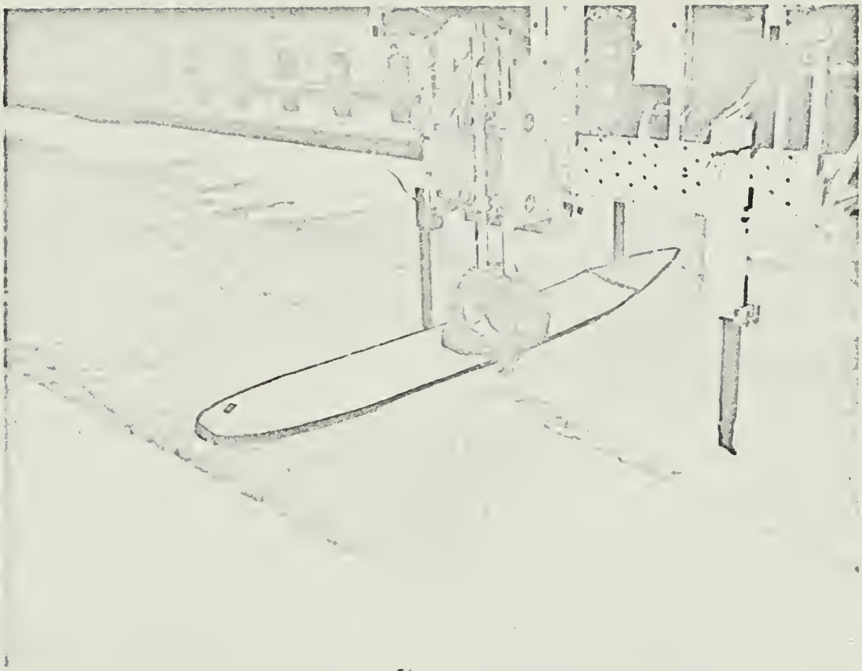


Fig. 7 Leeward side, model in a 30 knot sea state. Model velocity = zero.

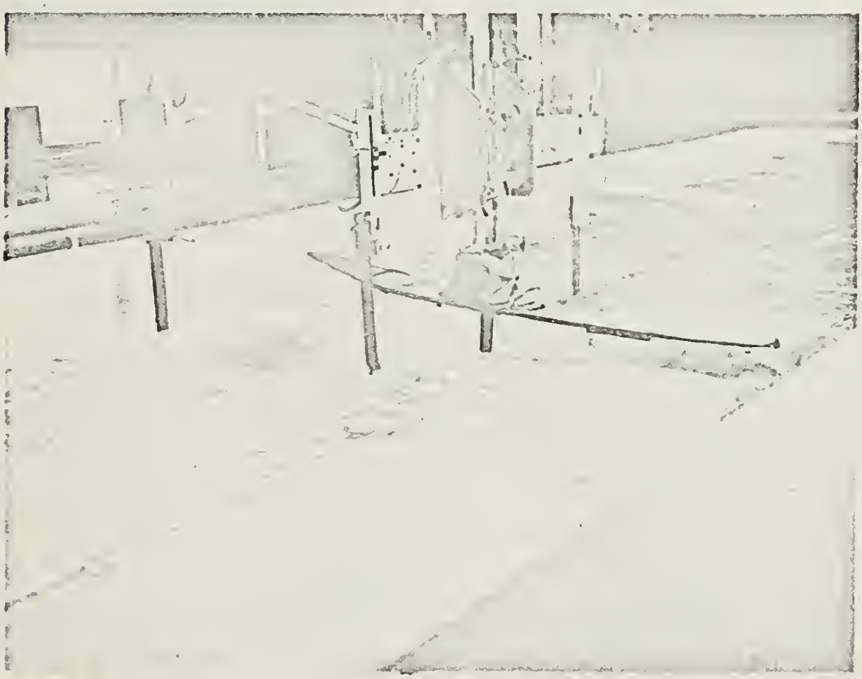


Fig. 8 Windward side, model in a 30 knot sea state. Model velocity = zero.

# APPENDIX D

## DETERMINATION OF THE NATURAL PERIOD OF ROLL

Because different loading conditions will affect the natural roll period of the actual ship, only an approximate figure was desired for the roll period. The following approximation for undamped roll was used:

$$T_{roll} = \frac{1.108k}{\sqrt{GM}}$$

where k is the transverse radius of gyration

A value for k equal to 0.40B, where B = the beam of the ship, was felt to be accurate enough for this experiment. Substituting 75.1 feet for B:

$$k = 30 \text{ ft.}$$

No data pertaining to the GM of the *American Racer* could be found so a GM = 5.5 feet for a *Mariner* class ship was substituted. The ships are reasonably similar, and as mentioned above, different loading conditions obviated a "correct" roll period.

Substituting:

$$T_{roll} = \frac{(1.108)(30)}{\sqrt{5.5}} = \underline{14.3 \text{ seconds}}$$

For the model:

$$T_{roll} = \frac{T_{roll} \text{ of the ship}}{\sqrt{\lambda}} = \frac{14.3}{\sqrt{96}} = \underline{1.44 \text{ seconds}}$$

The damped natural roll period of the model was made to match this figure by shifting ballast. It was felt that 1.44 seconds or 14.3 seconds full scale approximated to an acceptable degree a typical roll period for such a ship type. Damping was not taken into account because approximate roll scaling was felt to satisfy the experimental requirements.

# APPENDIX E

## MODEL TEST PROGRAM

| Condition | Sea State | Quantitites Measured |
|---|---|---|
| Model speed = 0 and 2.03 knots | Regular seas, $h/\lambda = 1/100$ | Wave heights at the bow, lee, and wake positions plus peak-to-peak roll |
| | 20 knot<br>25 knot<br>30 knot | Wave heights at the bow, lee, and wake positions plus peak-to-peak roll |
| | 30 knot | Heave |
| Model speed = 2.03 knots only | 30 knot | Bending Moment |
| *HEAD SEAS:* | | |
| Model speed = 2.03 knots | 30 knot | Bending Moment |

# APPENDIX F

## VALUES FOR THE SIGNIFICANT HEIGHTS ($H^{1/3}$)

| | WIND SPEED (knots) | SHIP SPEED (knots) | RESPONSE |
|---|---|---|---|
| Pierson-Moskowitz Wave Spectra | 20 | -- | 7.42' |
| | 25 | -- | 11.59' |
| | 30 | -- | 16.68' |
| Wake Wave | 20 | 0.00 | 10.63' |
| | 20 | 2.03 | 7.29' |
| | 25 | 0.00 | 16.40' |
| | 25 | 2.03 | 12.20' |
| | 30 | 0.00 | 24.75' |
| | 30 | 2.03 | 20.40' |
| Lee Wave | 20 | 0.00 | 4.84' |
| | 20 | 2.03 | 4.73' |
| | 25 | 0.00 | 8.36' |
| | 25 | 2.03 | 7.90' |
| | 30 | 0.00 | 17.90' |
| | 30 | 2.03 | 14.22' |
| Bow Wave | 20 | 0.00 | 10.40' |
| | 20 | 2.03 | 7.57' |
| | 25 | 0.00 | 15.10' |
| | 25 | 2.03 | 12.09' |
| | 30 | 0.00 | 20.81' |
| | 30 | 2.03 | 18.22' |
| Roll | 20 | 0.00 | 7.35° |
| | 20 | 2.03 | 7.49° |
| | 25 | 0.00 | 10.90° |
| | 25 | 2.03 | 12.03° |
| | 30 | 0.00 | 13.20° |
| | 30 | 2.03 | 9.72° |
| Heave | 30 | 0.00 | 12.78' |
| | 30 | 2.03 | 12.58' |

# APPENDIX G

## GRAPHICAL PRESENTATION OF RESULTS

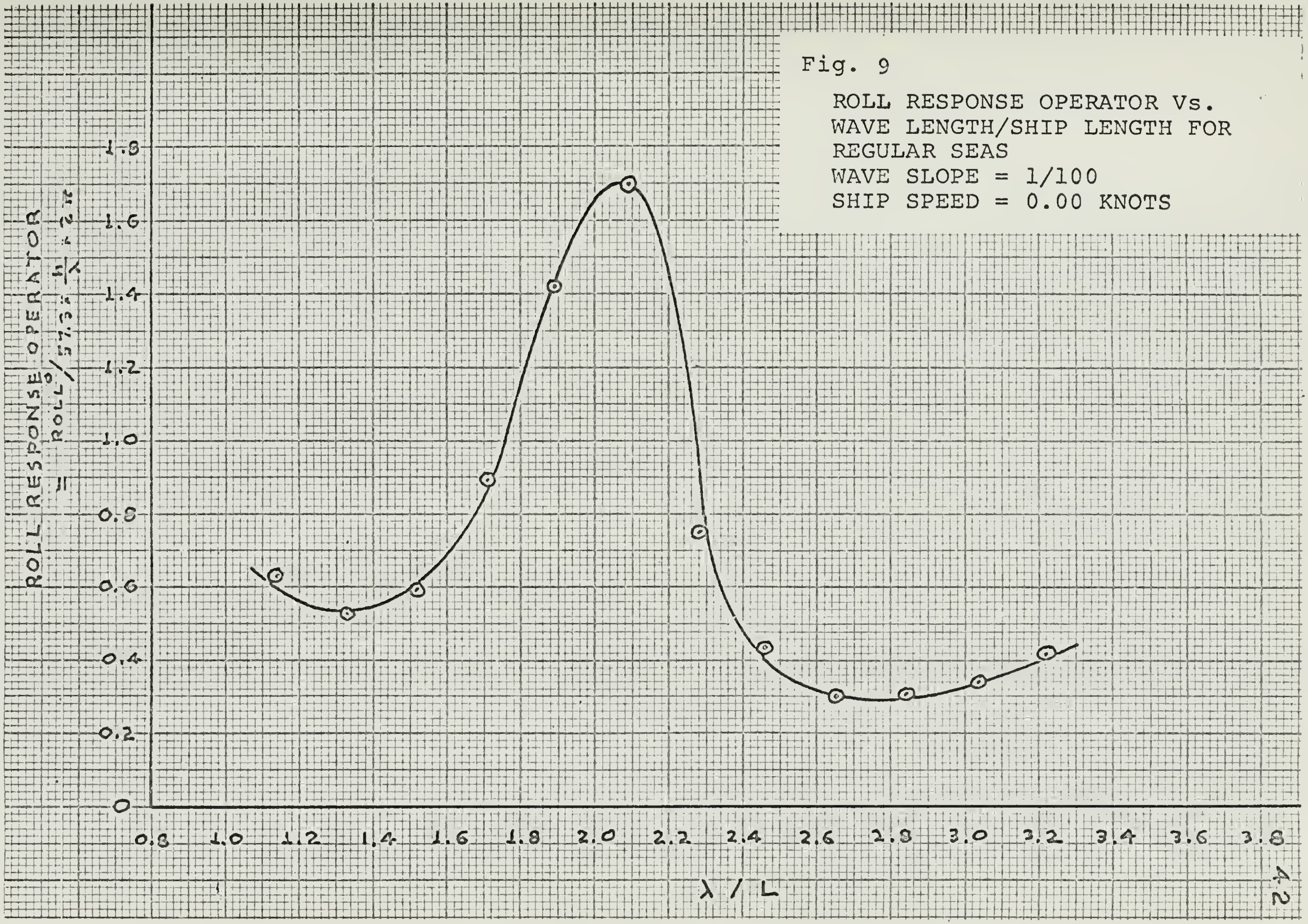



Fig. 9

ROLL RESPONSE OPERATOR Vs.
WAVE LENGTH/SHIP LENGTH FOR
REGULAR SEAS
WAVE SLOPE = 1/100
SHIP SPEED = 0.00 KNOTS

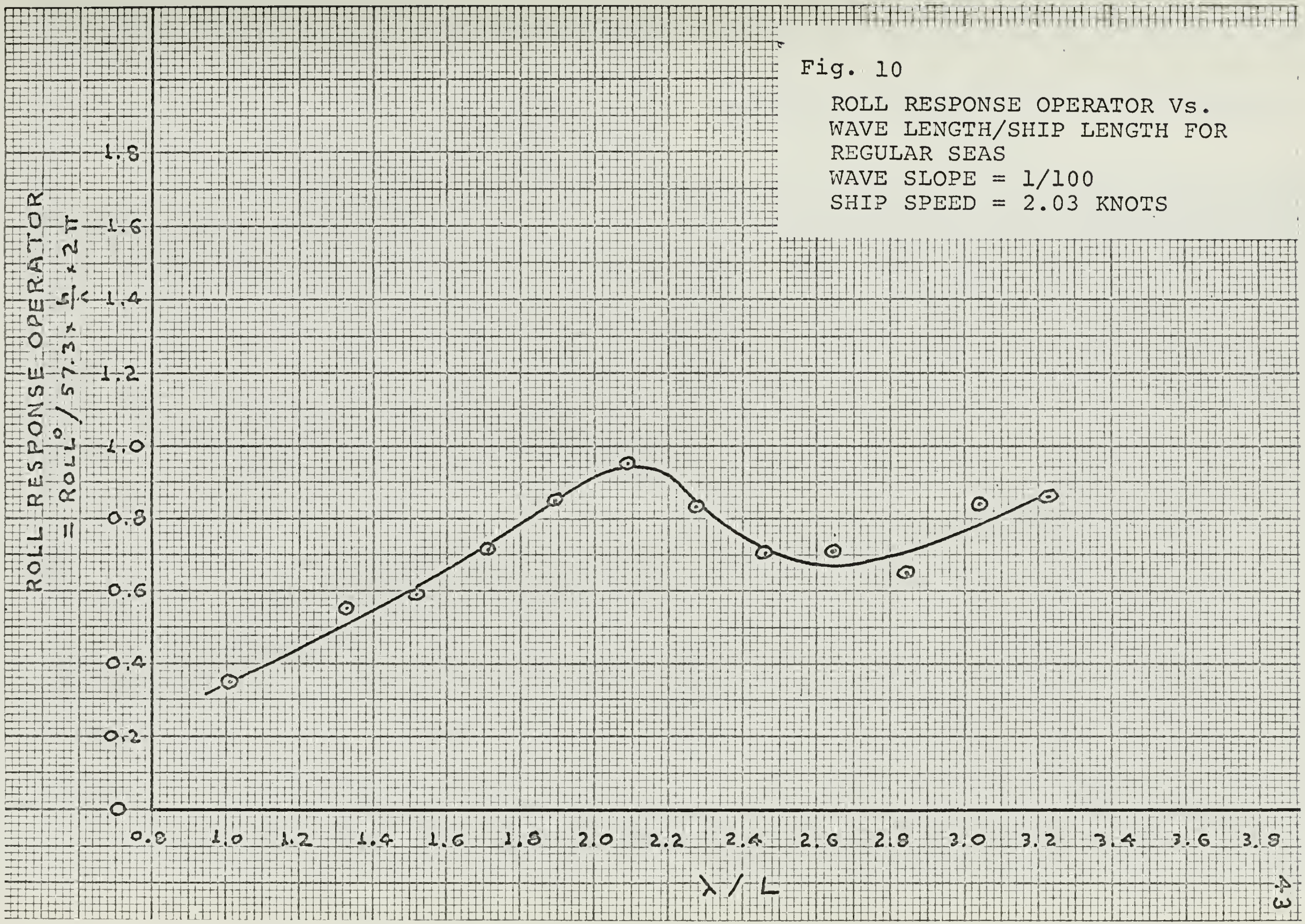



Fig. 10

ROLL RESPONSE OPERATOR Vs. WAVE LENGTH/SHIP LENGTH FOR REGULAR SEAS
WAVE SLOPE = 1/100
SHIP SPEED = 2.03 KNOTS

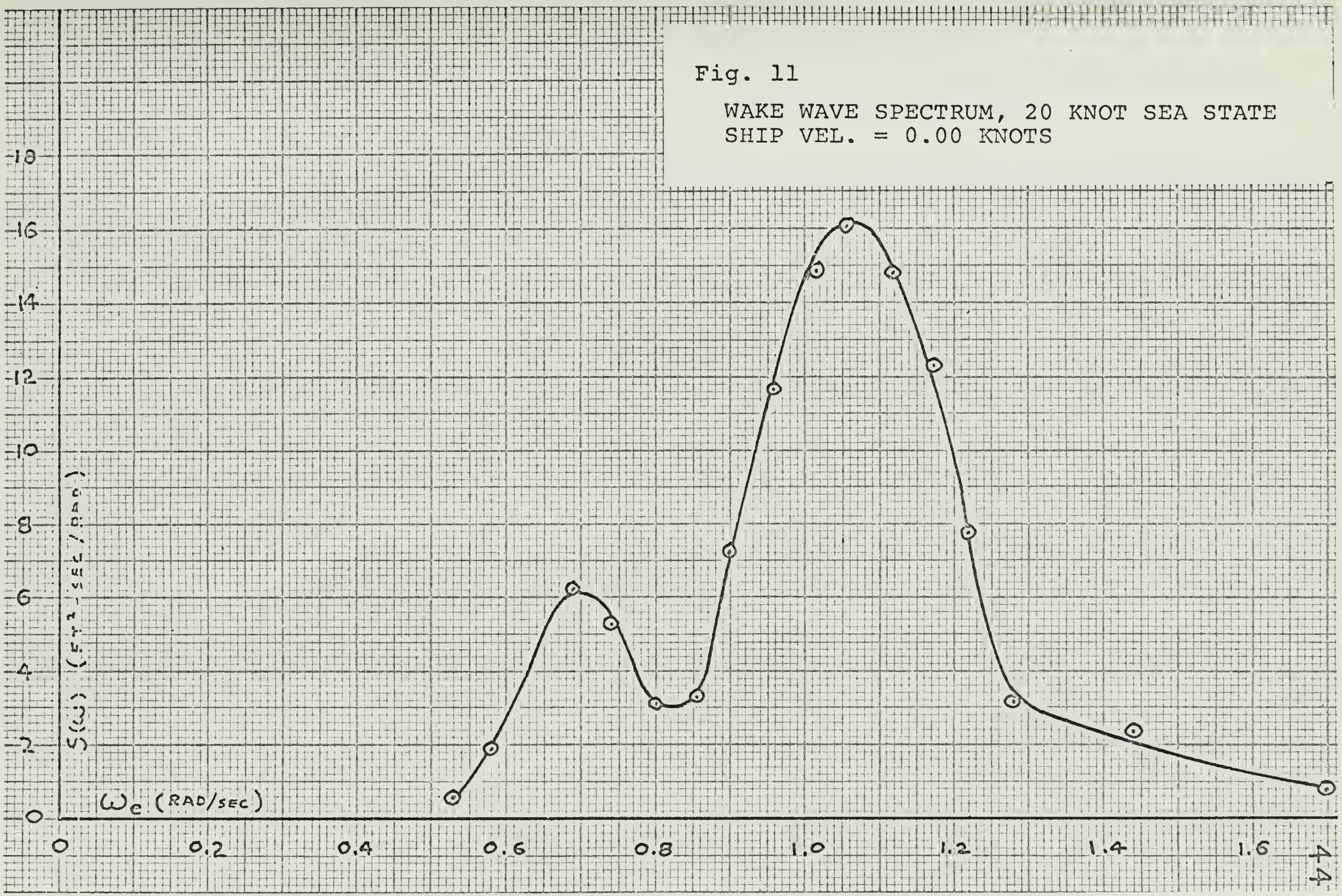



Fig. 11

WAKE WAVE SPECTRUM, 20 KNOT SEA STATE
SHIP VEL. = 0.00 KNOTS

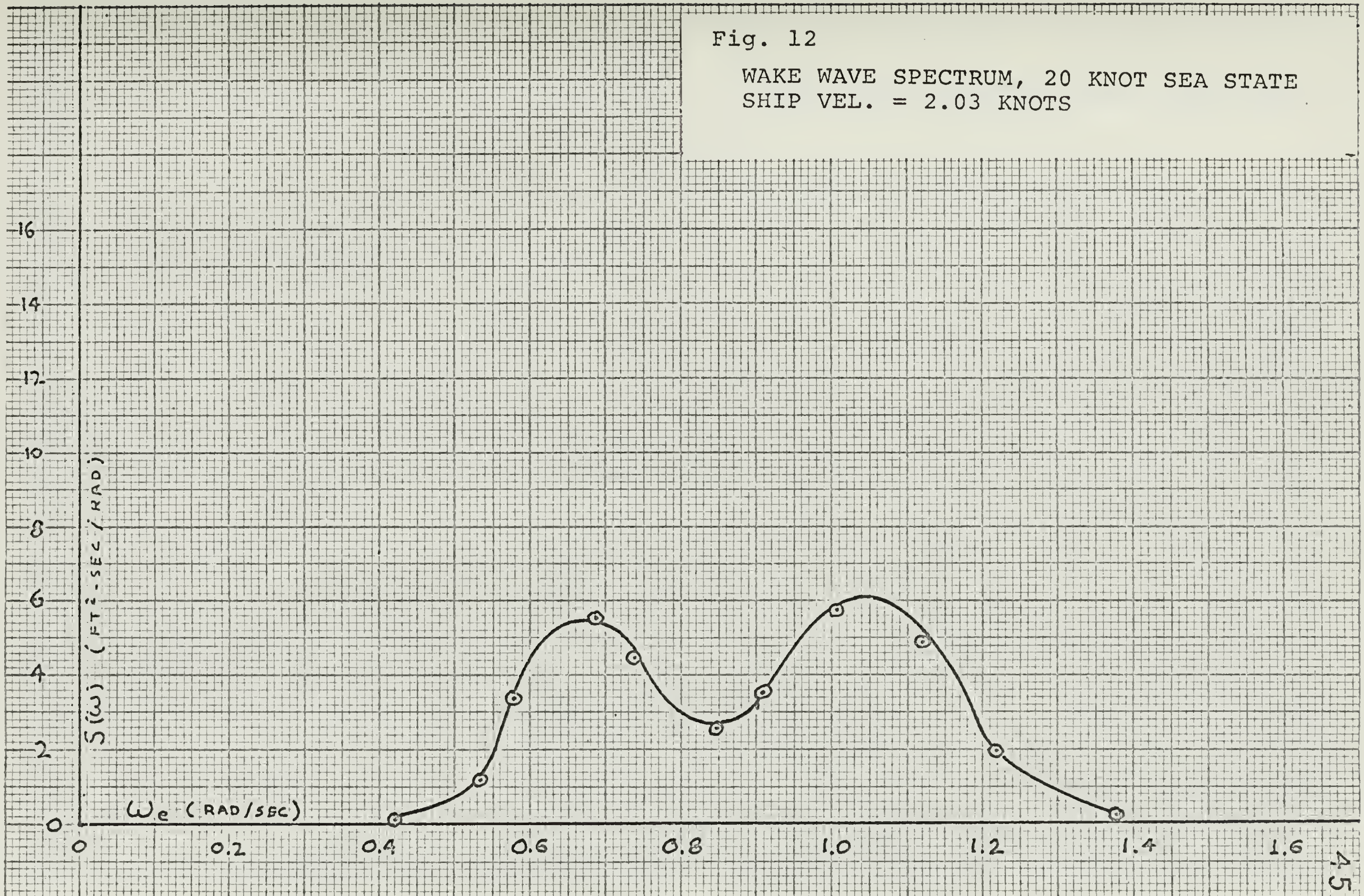



Fig. 12

WAKE WAVE SPECTRUM, 20 KNOT SEA STATE
SHIP VEL. = 2.03 KNOTS

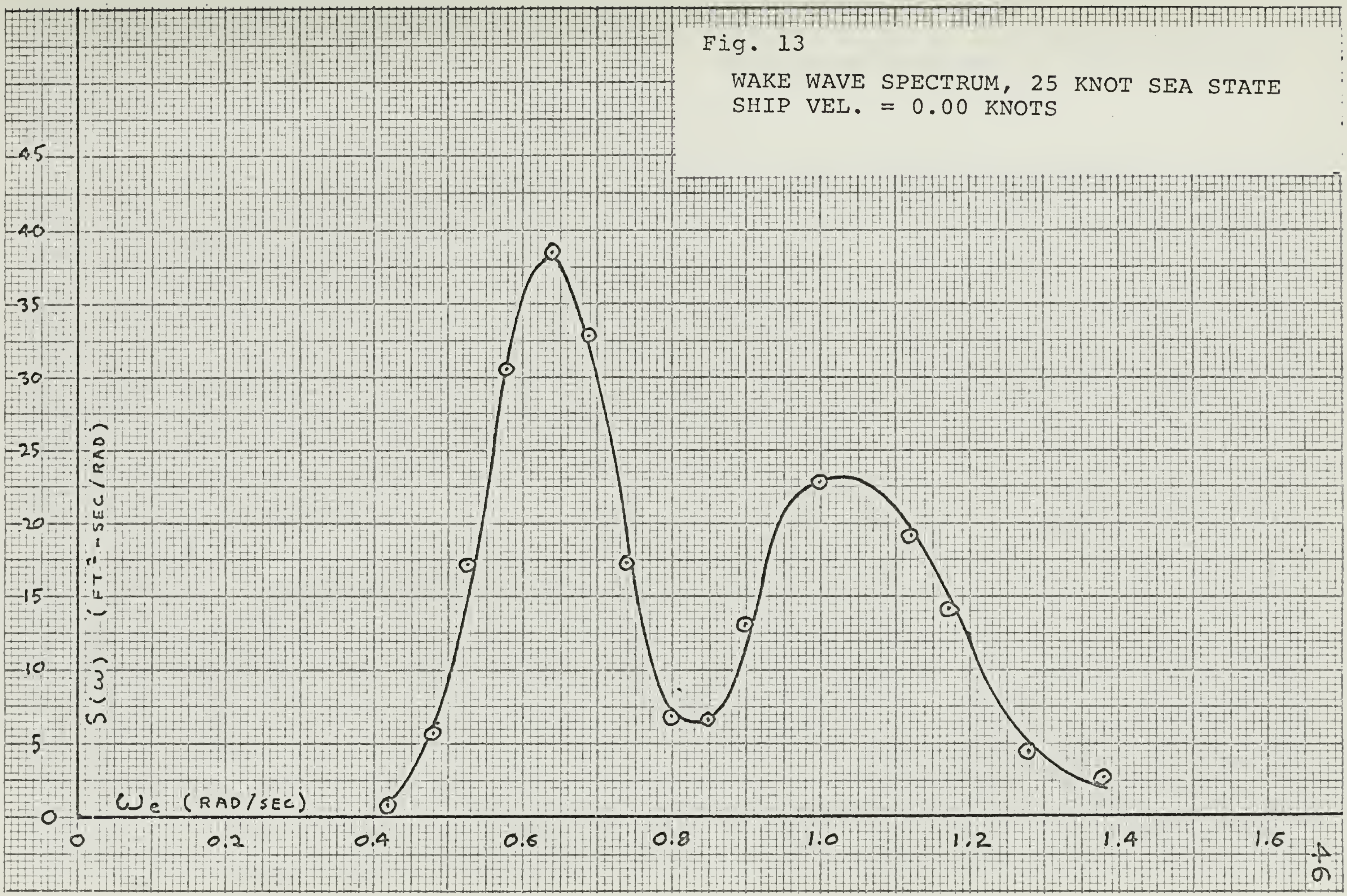
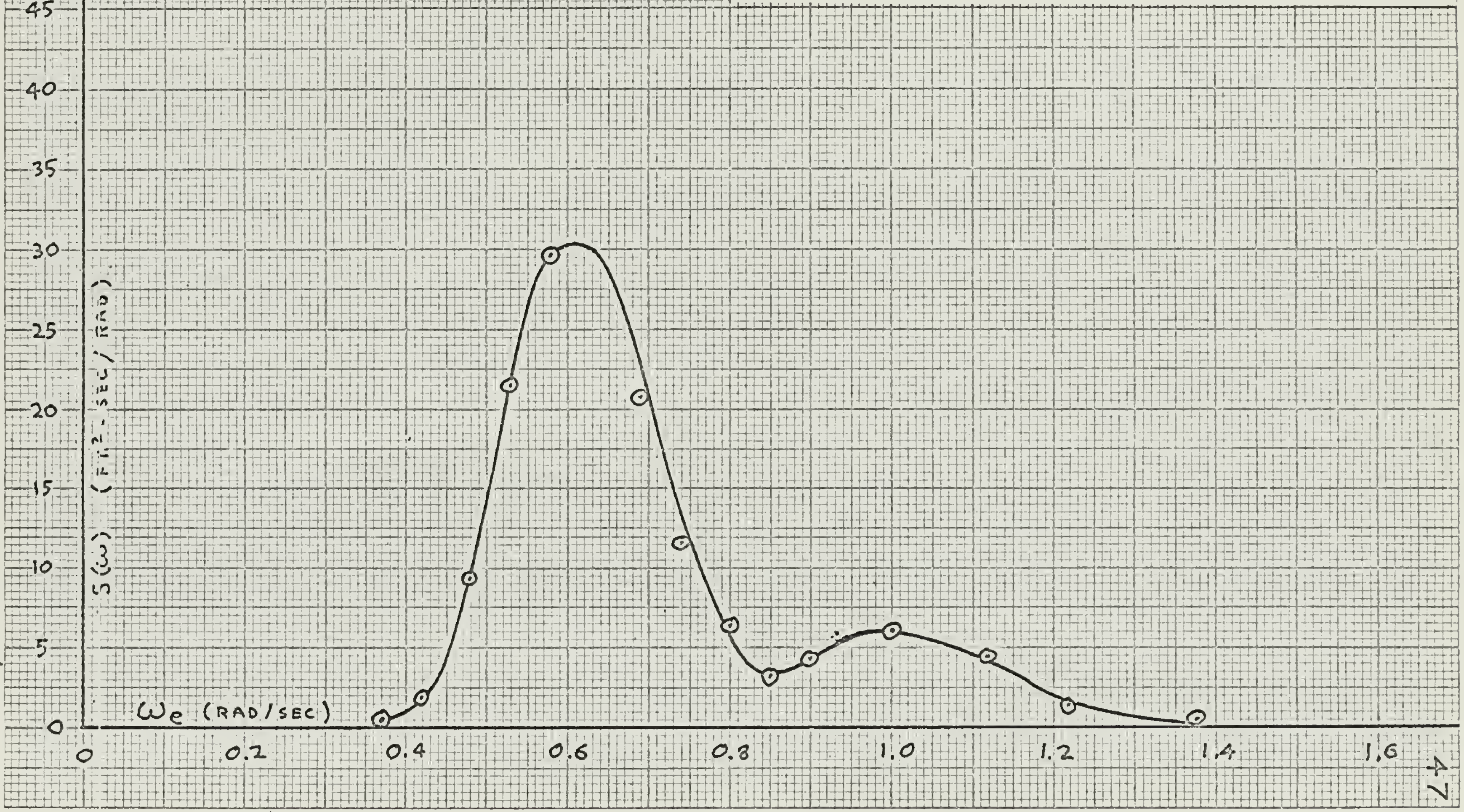



Fig. 13

WAKE WAVE SPECTRUM, 25 KNOT SEA STATE
SHIP VEL. = 0.00 KNOTS

Fig. 14

WAKE WAVE SPECTRUM, 25 KNOT SEA STATE
SHIP VEL. = 2.03 KNOTS



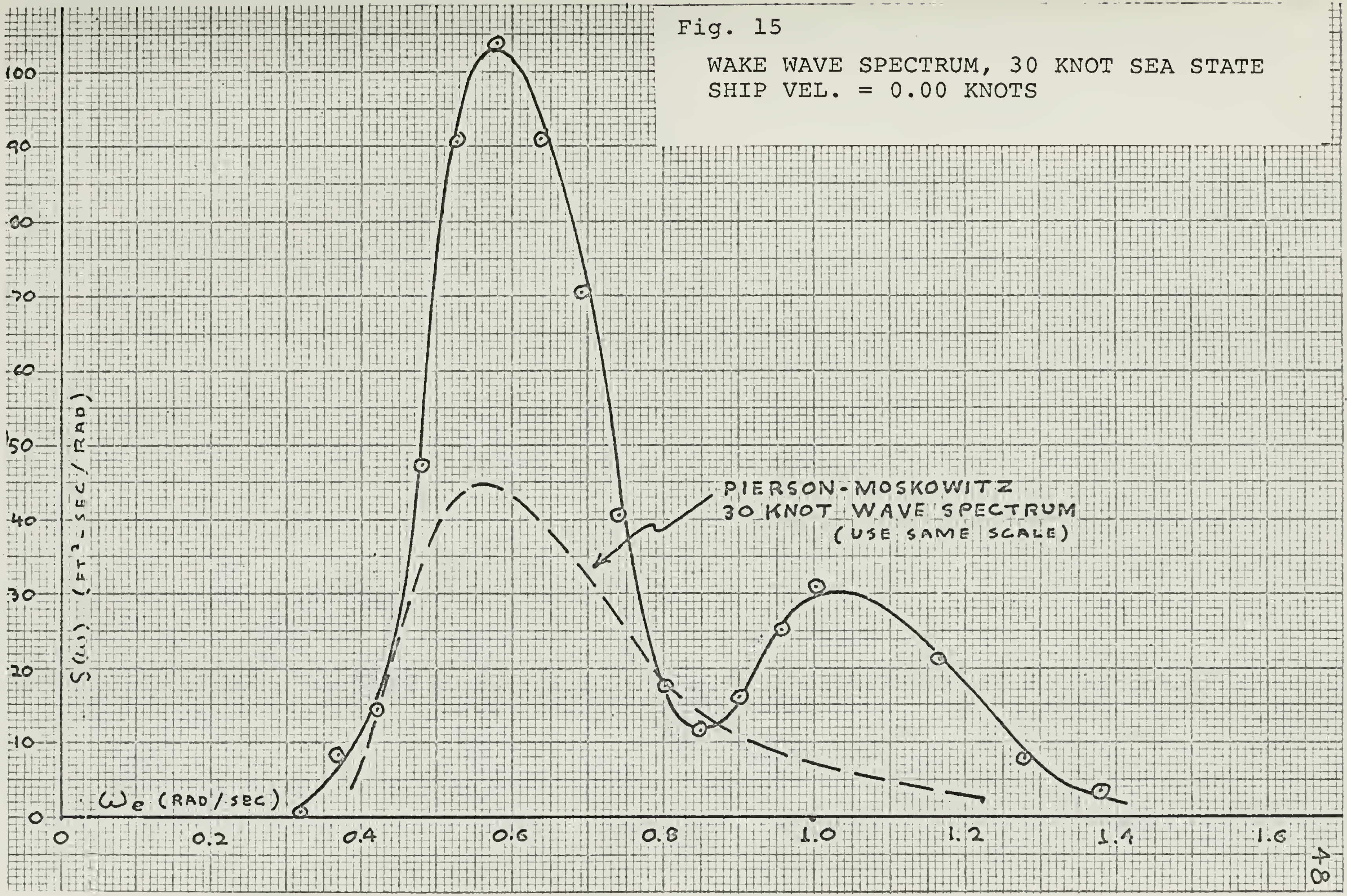



Fig. 15

WAKE WAVE SPECTRUM, 30 KNOT SEA STATE
SHIP VEL. = 0.00 KNOTS

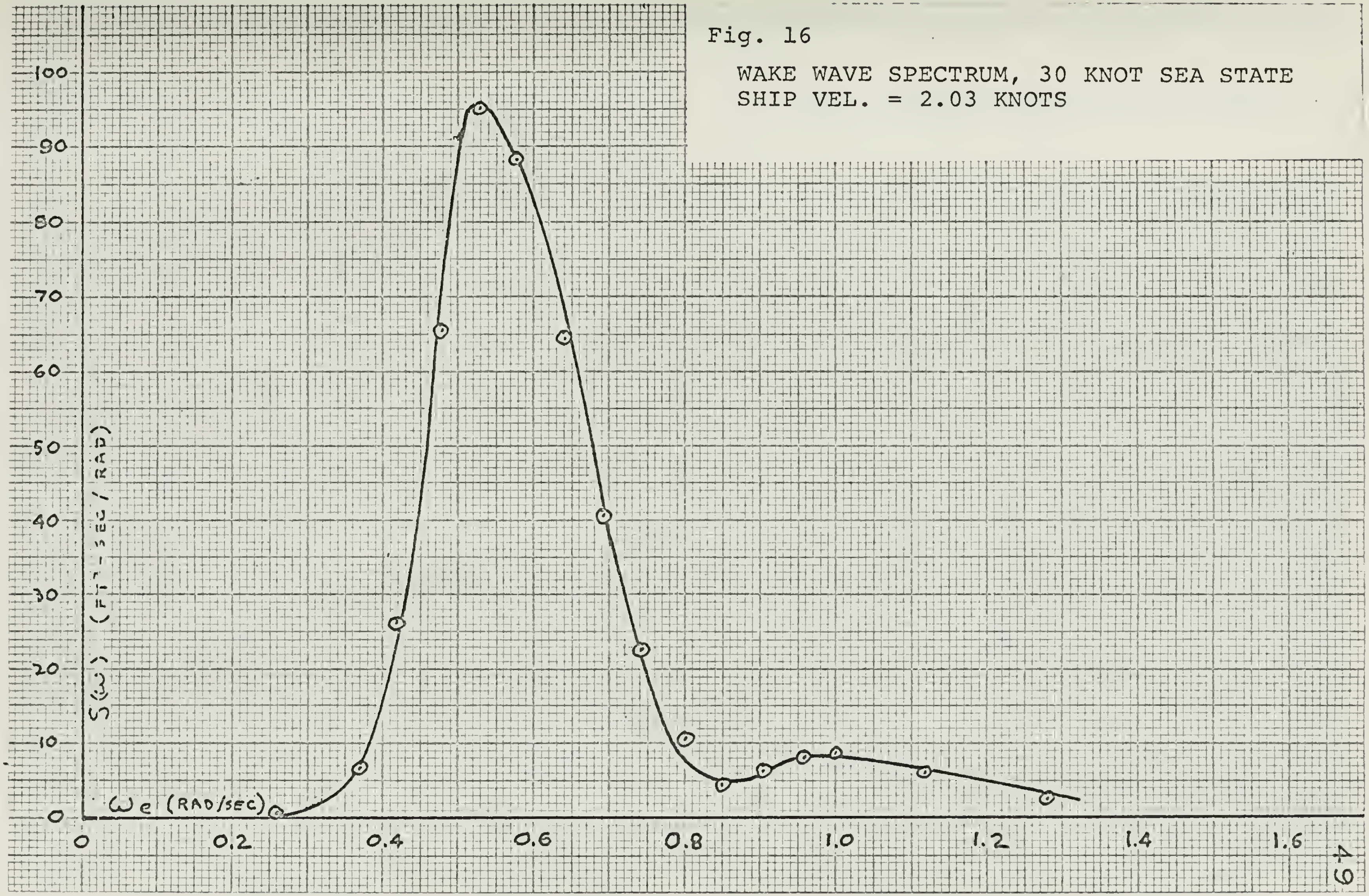
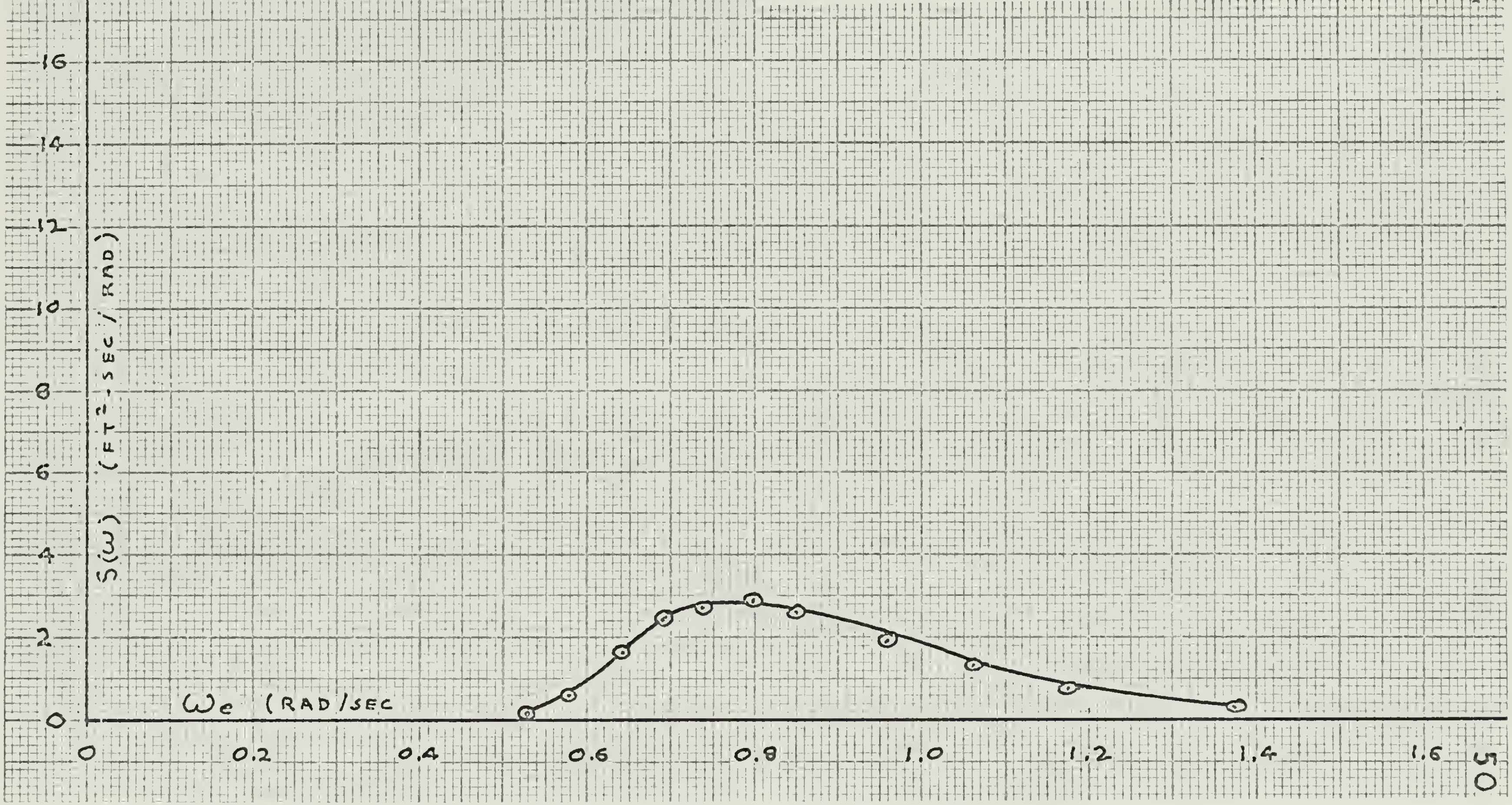



Fig. 16

WAKE WAVE SPECTRUM, 30 KNOT SEA STATE
SHIP VEL. = 2.03 KNOTS

Fig. 17

LEE WAVE SPECTRUM, 20 KNOT SEA STATE
SHIP VEL. = 0.00 KNOTS



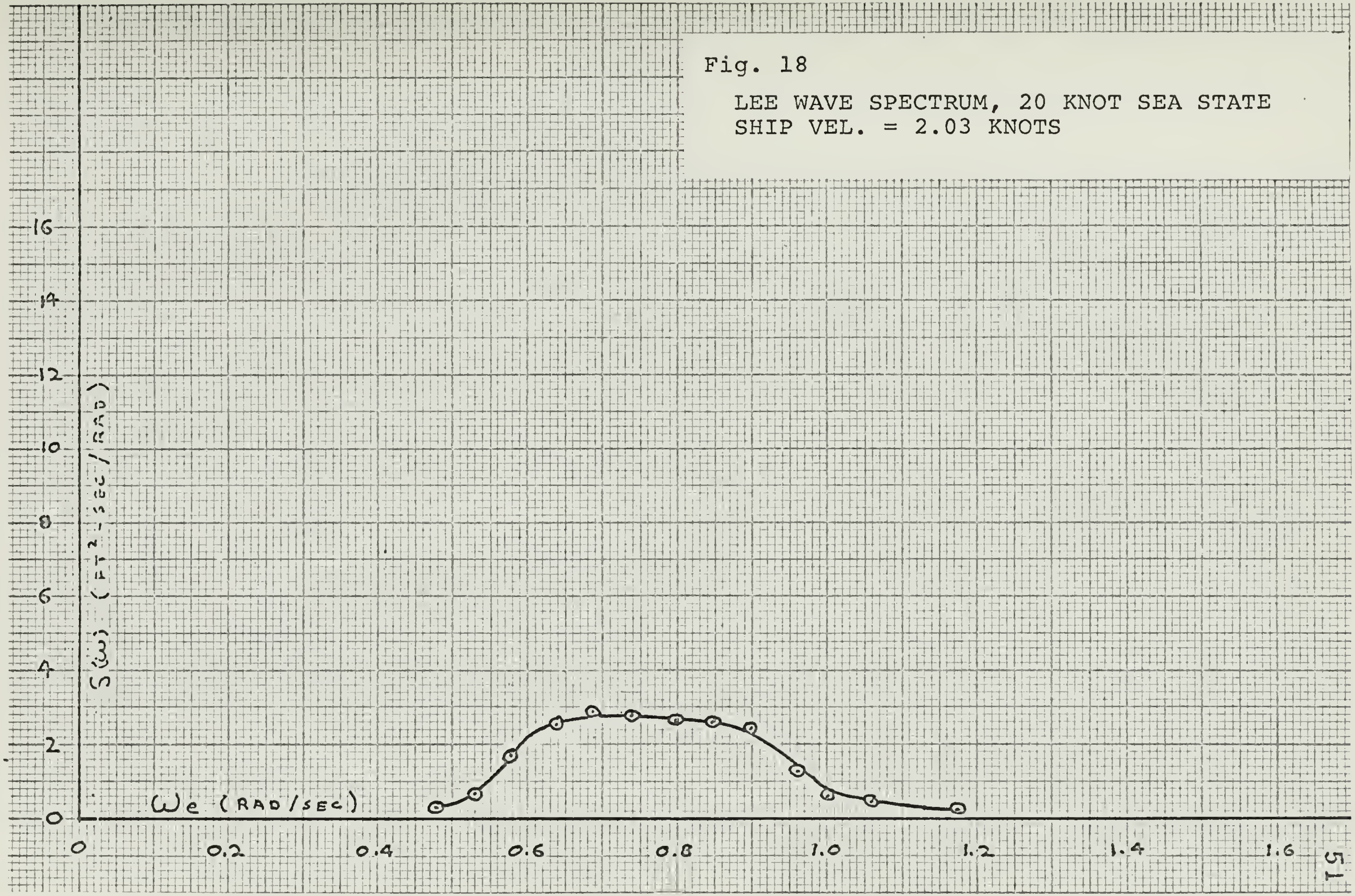
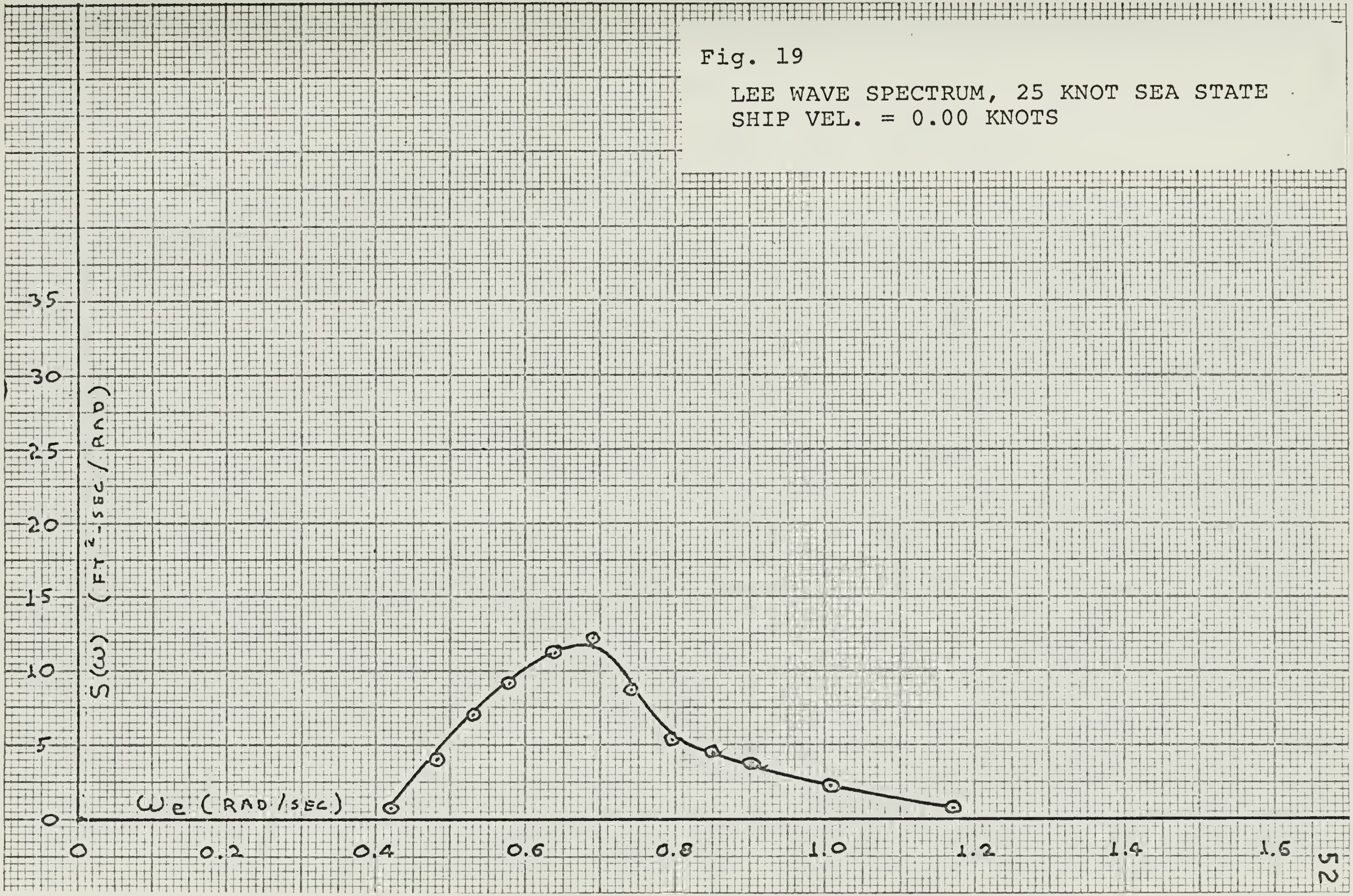



Fig. 18

LEE WAVE SPECTRUM, 20 KNOT SEA STATE
SHIP VEL. = 2.03 KNOTS

Fig. 19

LEE WAVE SPECTRUM, 25 KNOT SEA STATE
SHIP VEL. = 0.00 KNOTS



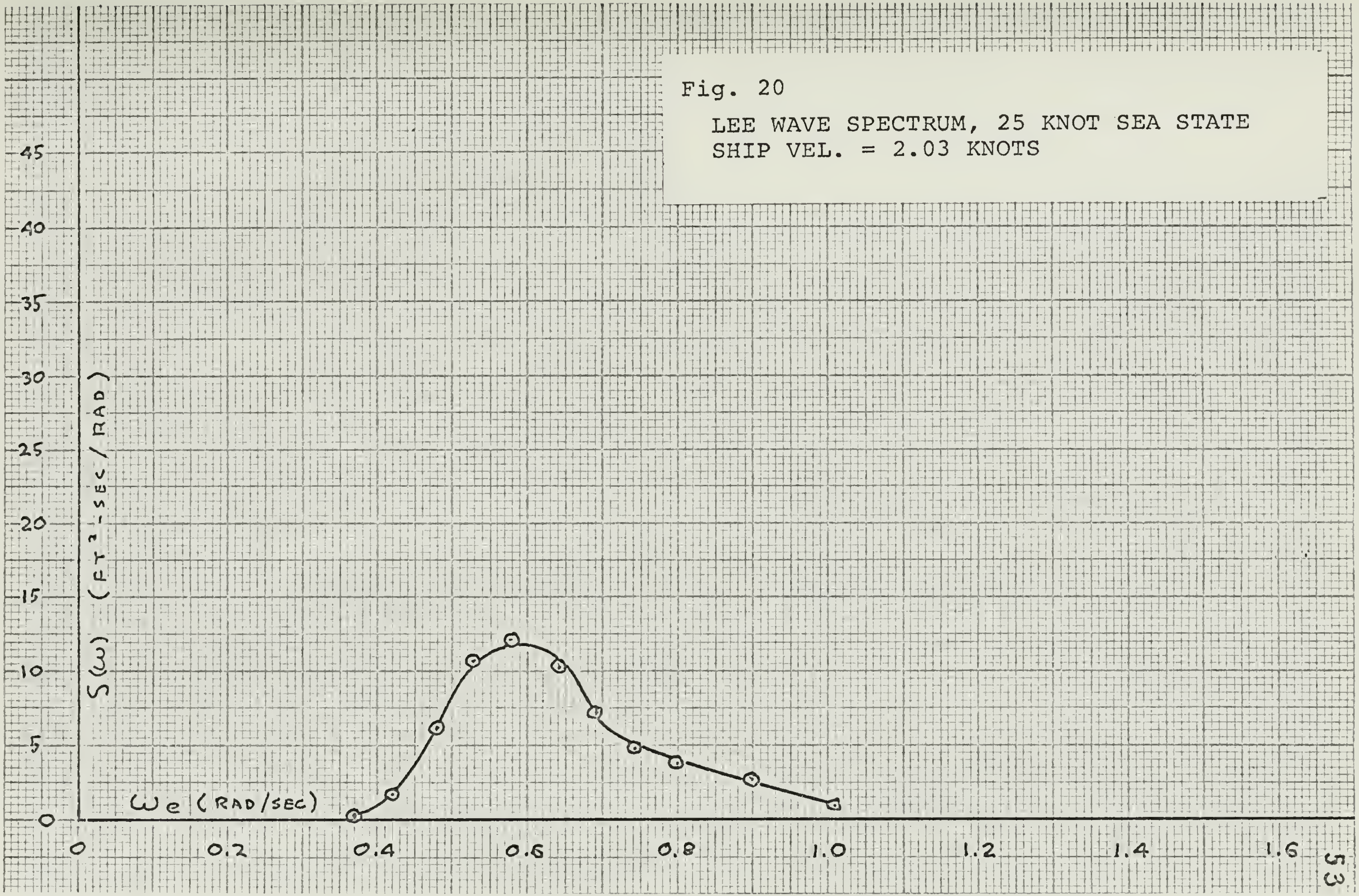



Fig. 20

LEE WAVE SPECTRUM, 25 KNOT SEA STATE
SHIP VEL. = 2.03 KNOTS

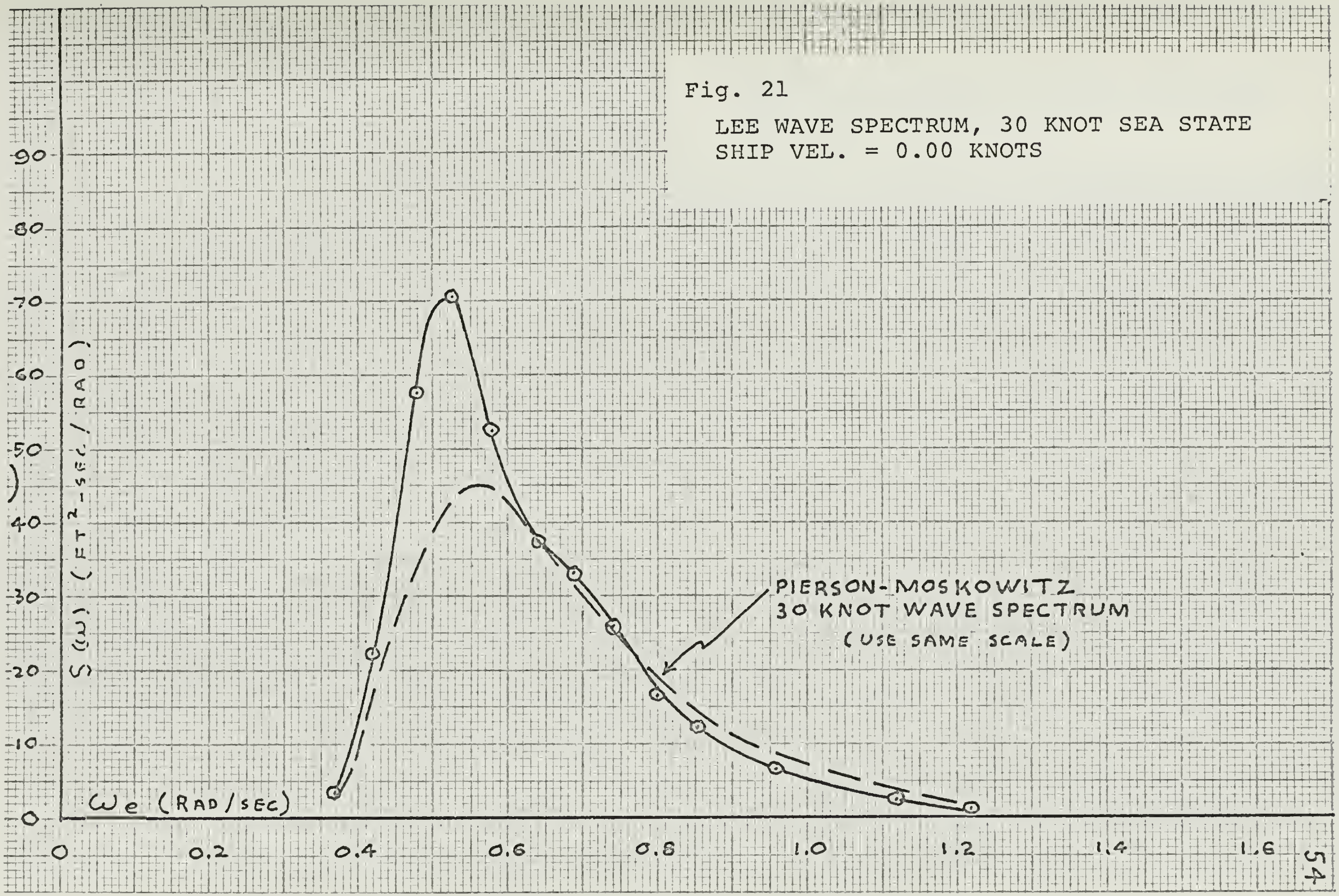



Fig. 21

LEE WAVE SPECTRUM, 30 KNOT SEA STATE
SHIP VEL. = 0.00 KNOTS

Fig. 22

LEE WAVE SPECTRUM, 30 KNOT SEA STATE
SHIP VEL. = 2.03 KNOTS

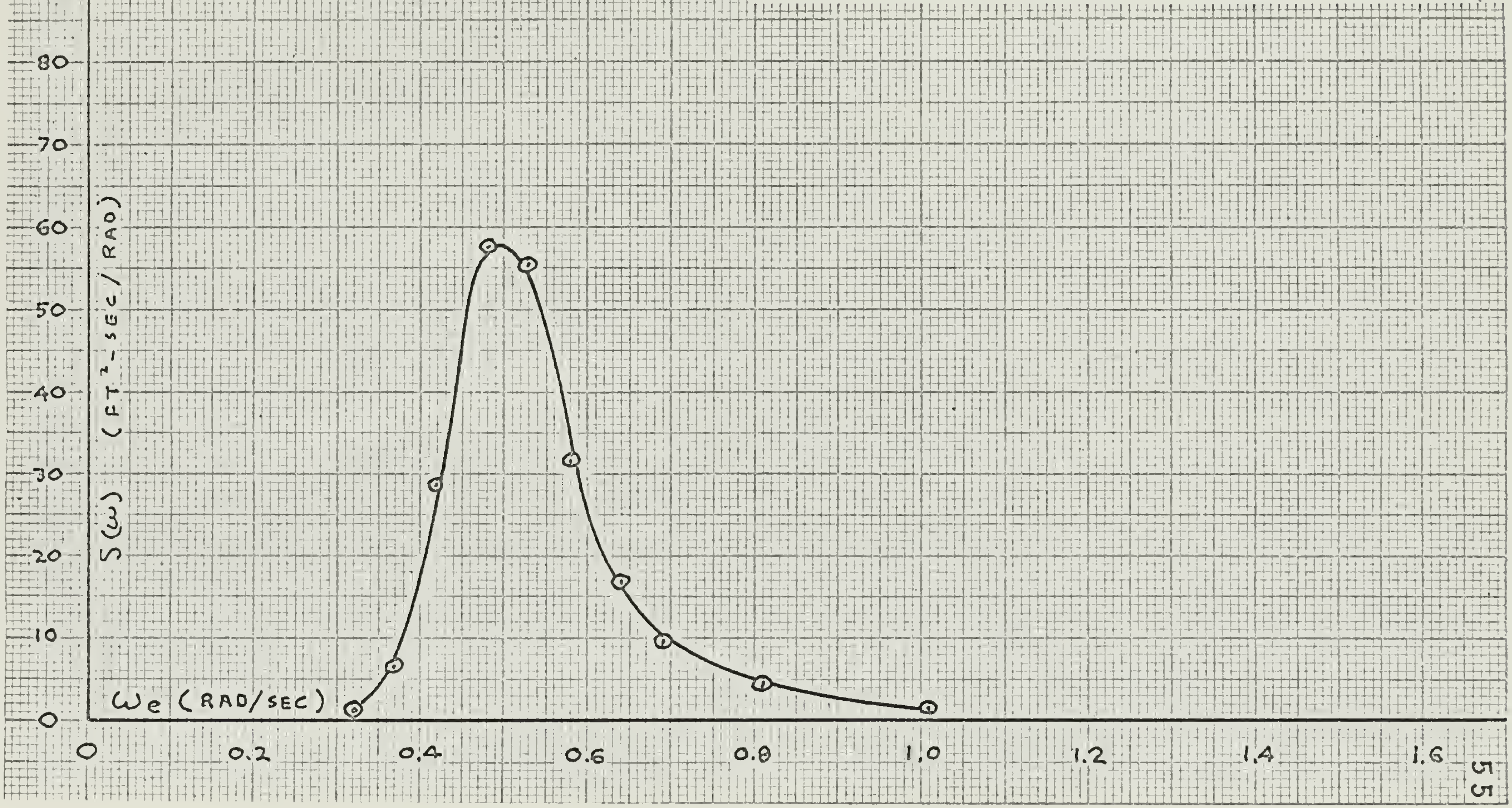
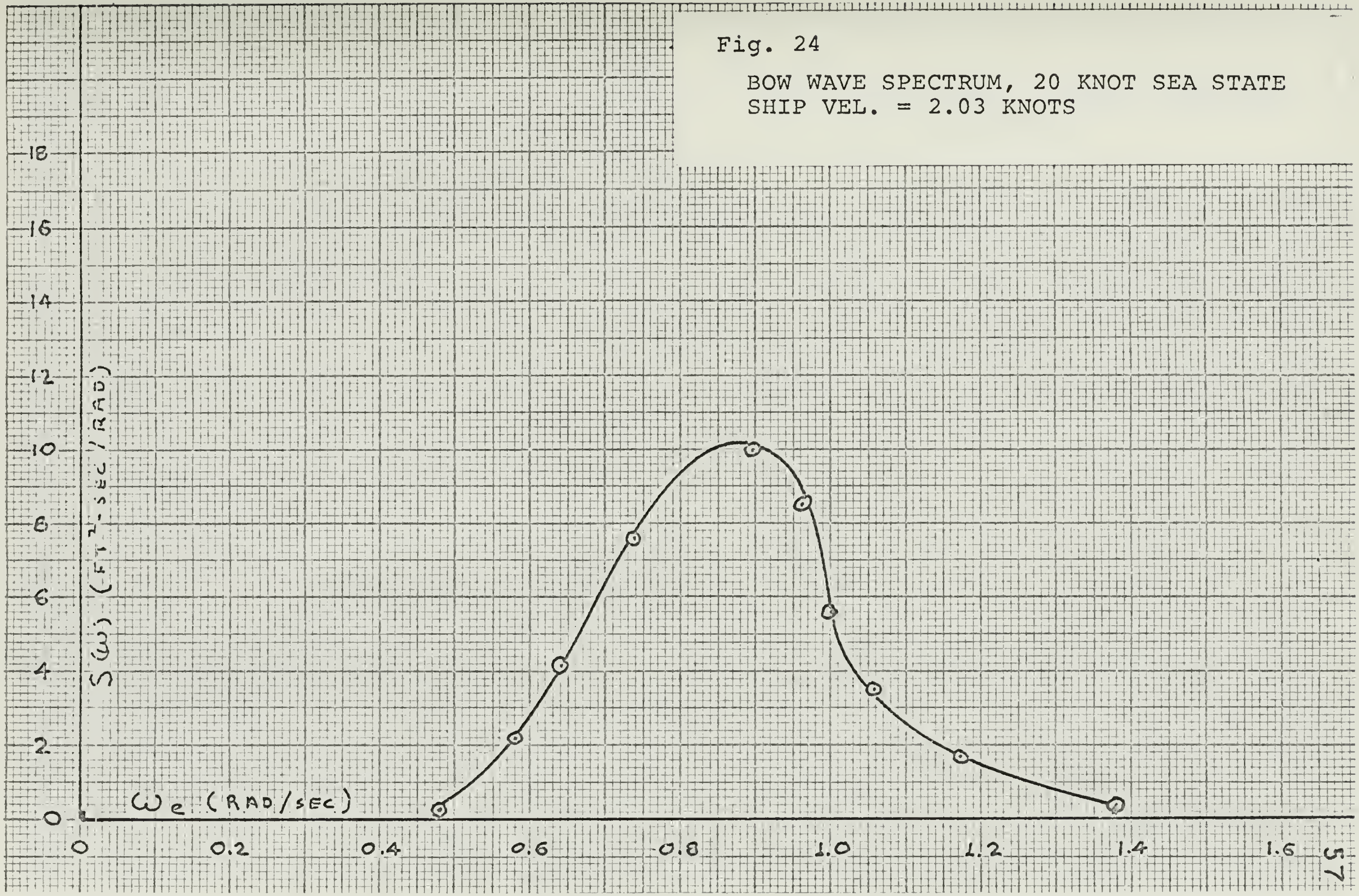


Fig. 23

BOW WAVE SPECTRUM, 20 KNOT SEA STATE
SHIP VEL. = 0.00 KNOTS

Fig. 24

BOW WAVE SPECTRUM, 20 KNOT SEA STATE
SHIP VEL. = 2.03 KNOTS



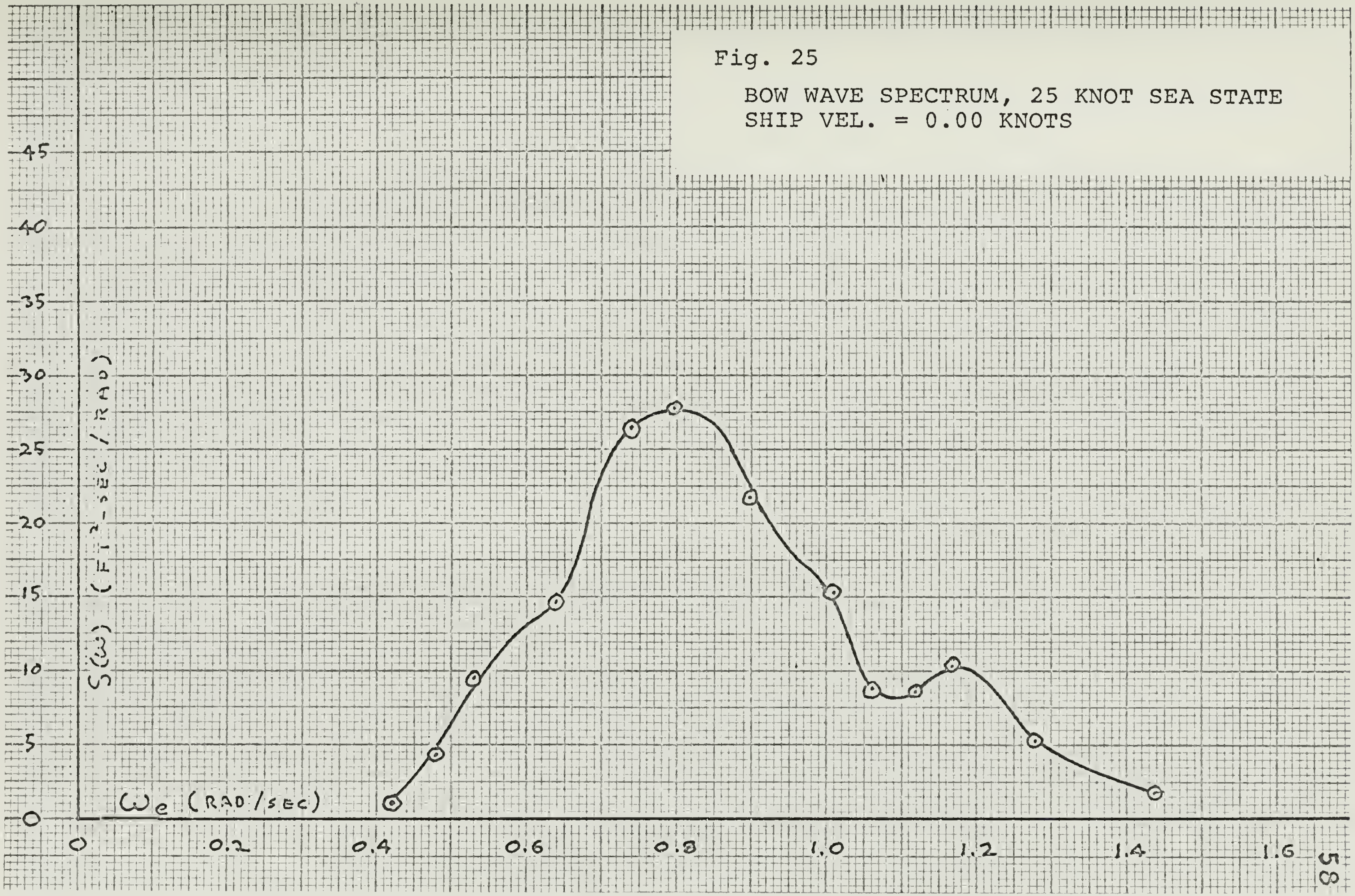



Fig. 25

BOW WAVE SPECTRUM, 25 KNOT SEA STATE
SHIP VEL. = 0.00 KNOTS

Fig. 26

BOW WAVE SPECTRUM, 25 KNOT SEA STATE
SHIP VEL. = 2.03 KNOTS

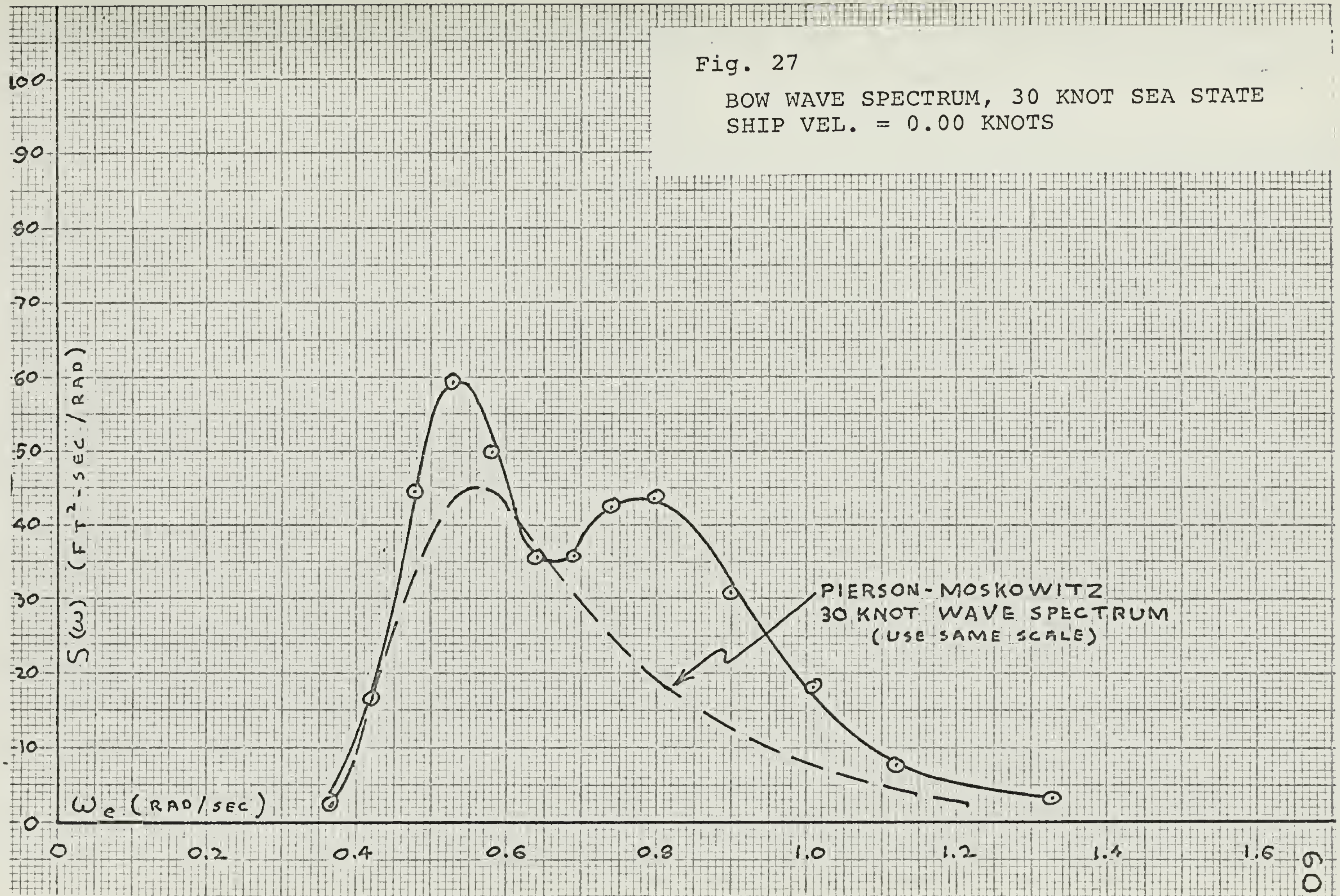



Fig. 27

BOW WAVE SPECTRUM, 30 KNOT SEA STATE
SHIP VEL. = 0.00 KNOTS

Fig. 28

BOW WAVE SPECTRUM, 30 KNOT SEA STATE
SHIP VEL. = 2.03 KNOTS

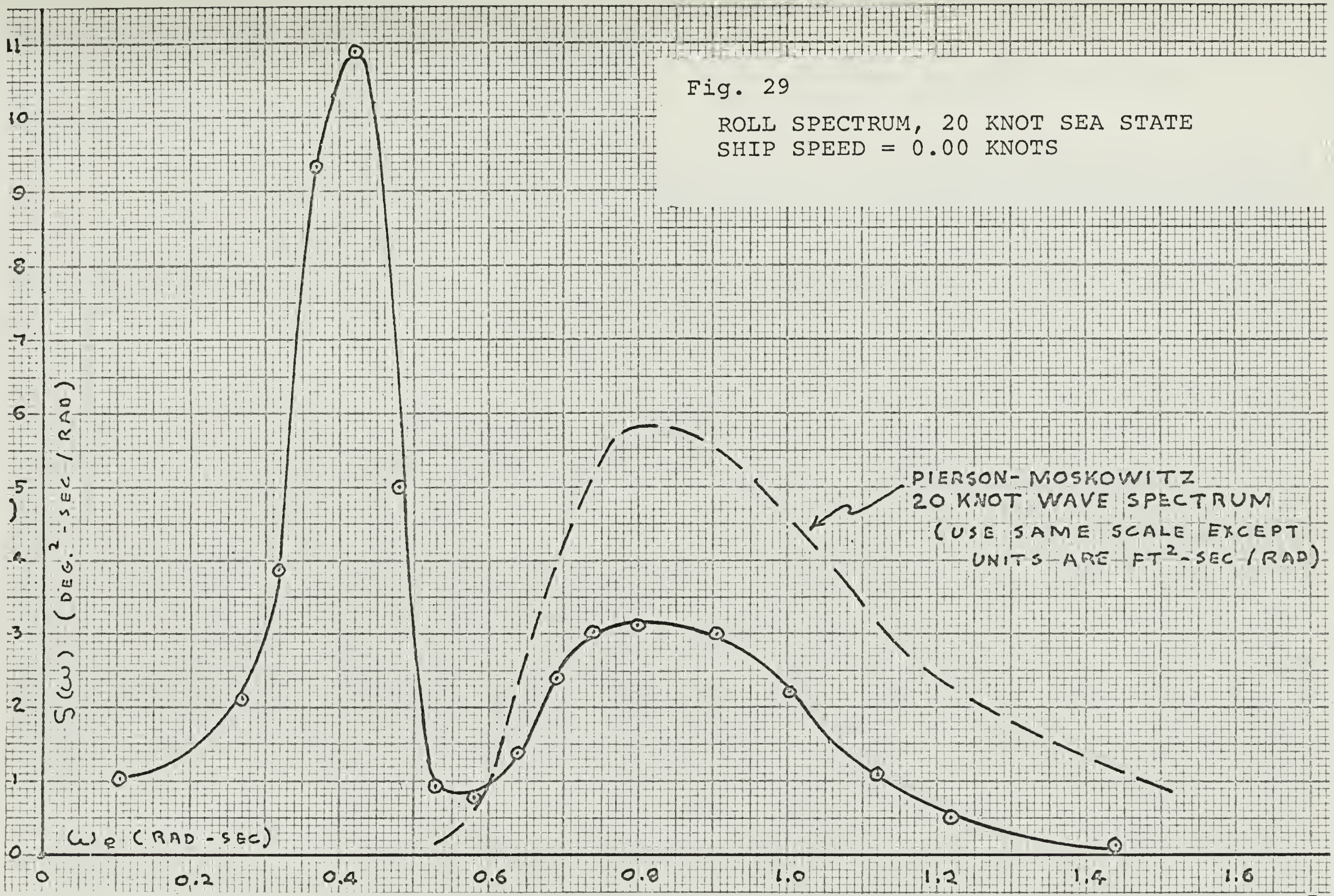



Fig. 29

ROLL SPECTRUM, 20 KNOT SEA STATE
SHIP SPEED = 0.00 KNOTS

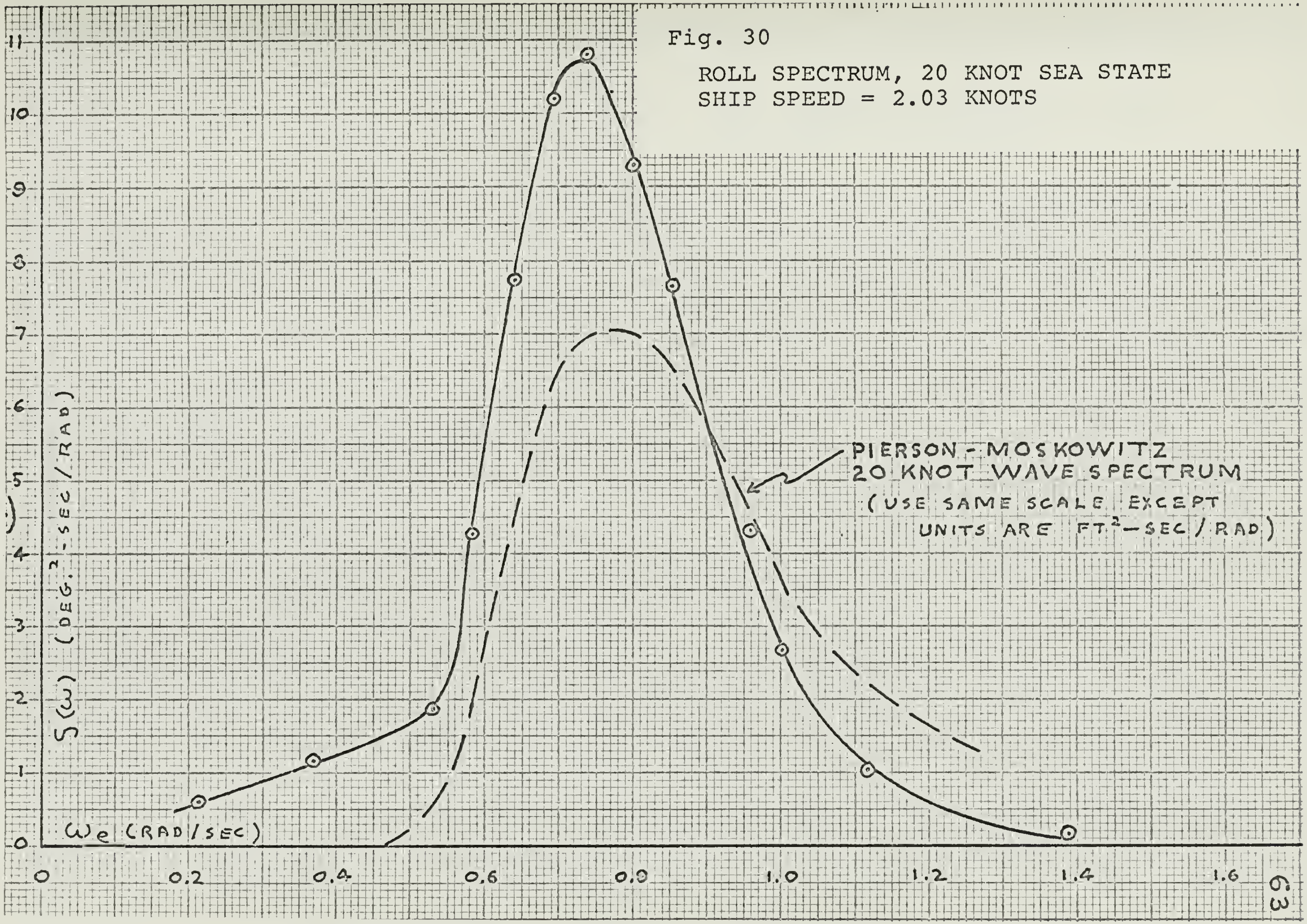



Fig. 30

ROLL SPECTRUM, 20 KNOT SEA STATE
SHIP SPEED = 2.03 KNOTS

Fig. 31

ROLL SPECTRUM, 25 KNOT SEA STATE
SHIP SPEED = 0.00 KNOTS

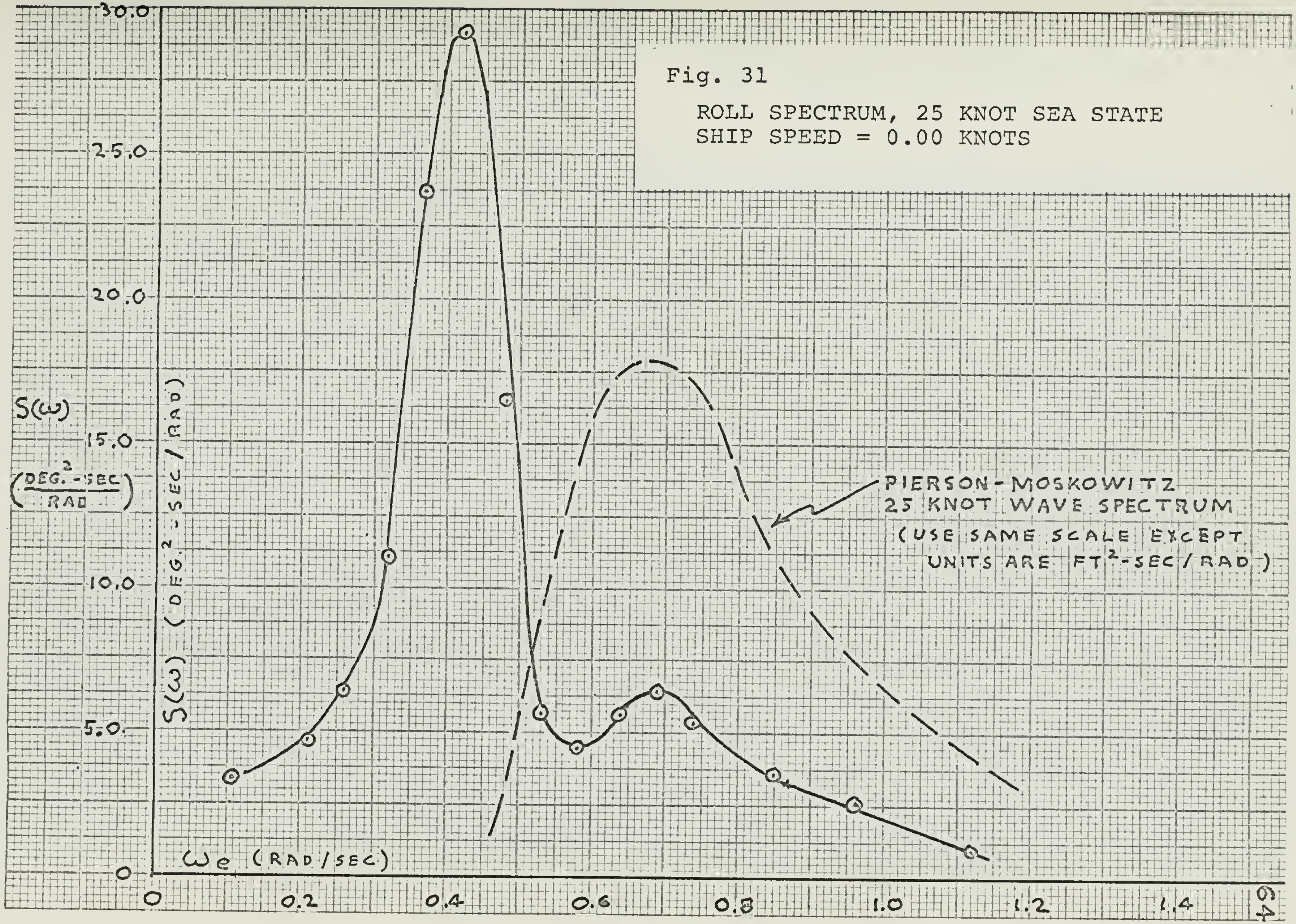


Fig. 32

ROLL SPECTRUM, 25 KNOT SEA STATE
SHIP SPEED = 2.03 KNOTS

Fig. 33

ROLL SPECTRUM, 30 KNOT SEA STATE
SHIP SPEED = 0.00 KNOTS

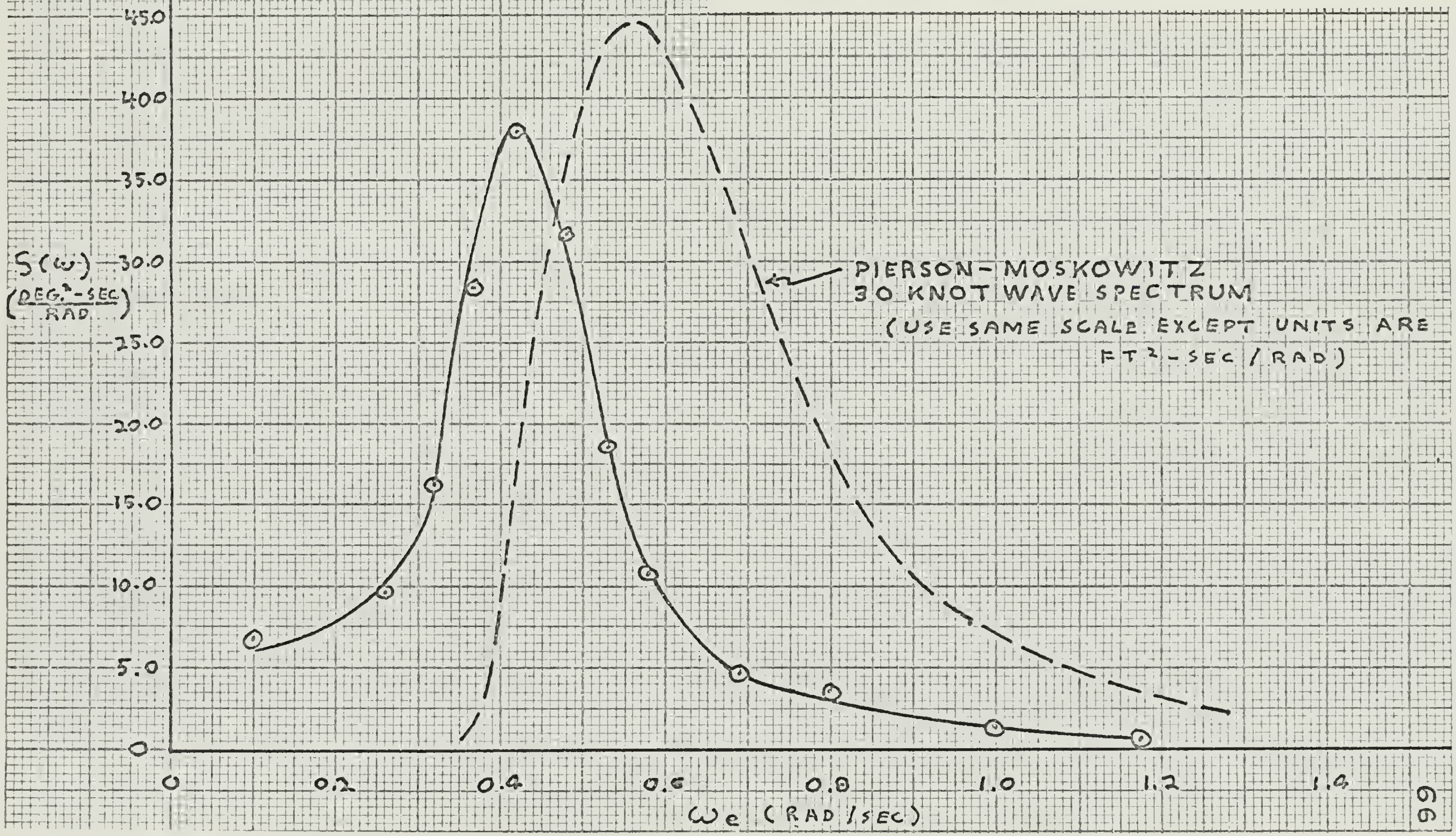
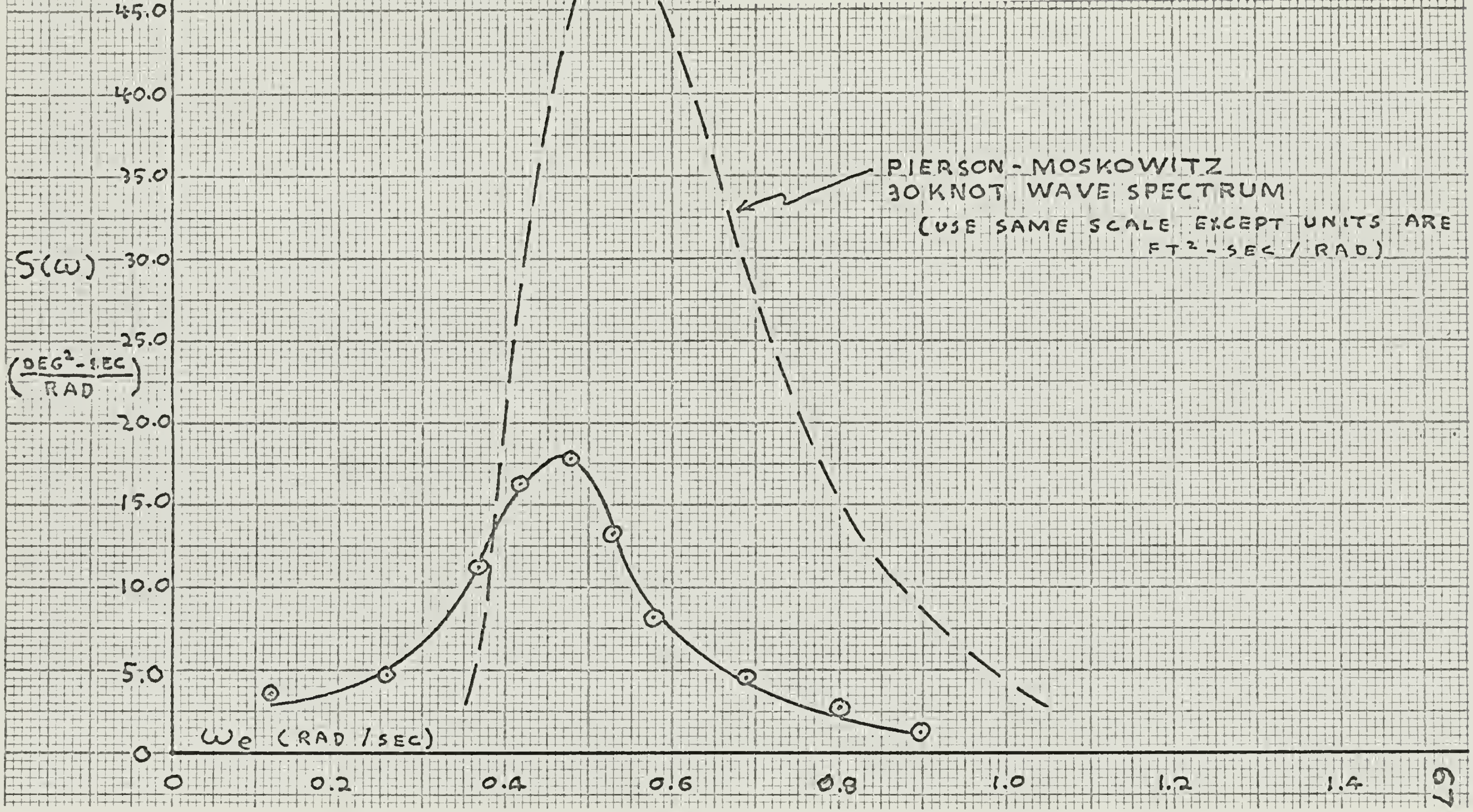


Fig. 34

ROLL SPECTRUM, 30 KNOT SEA STATE
SHIP SPEED = 2.03 KNOTS



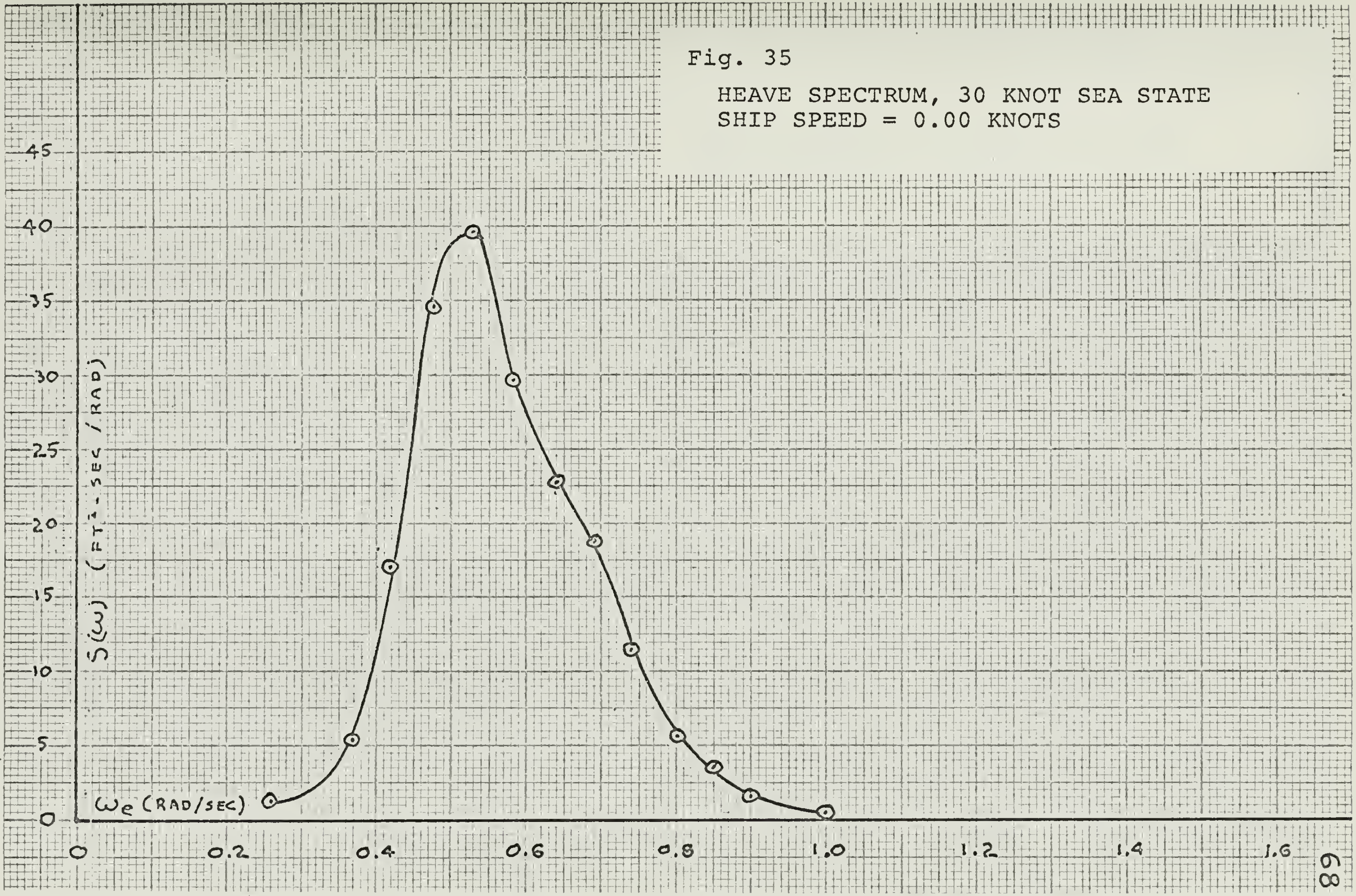
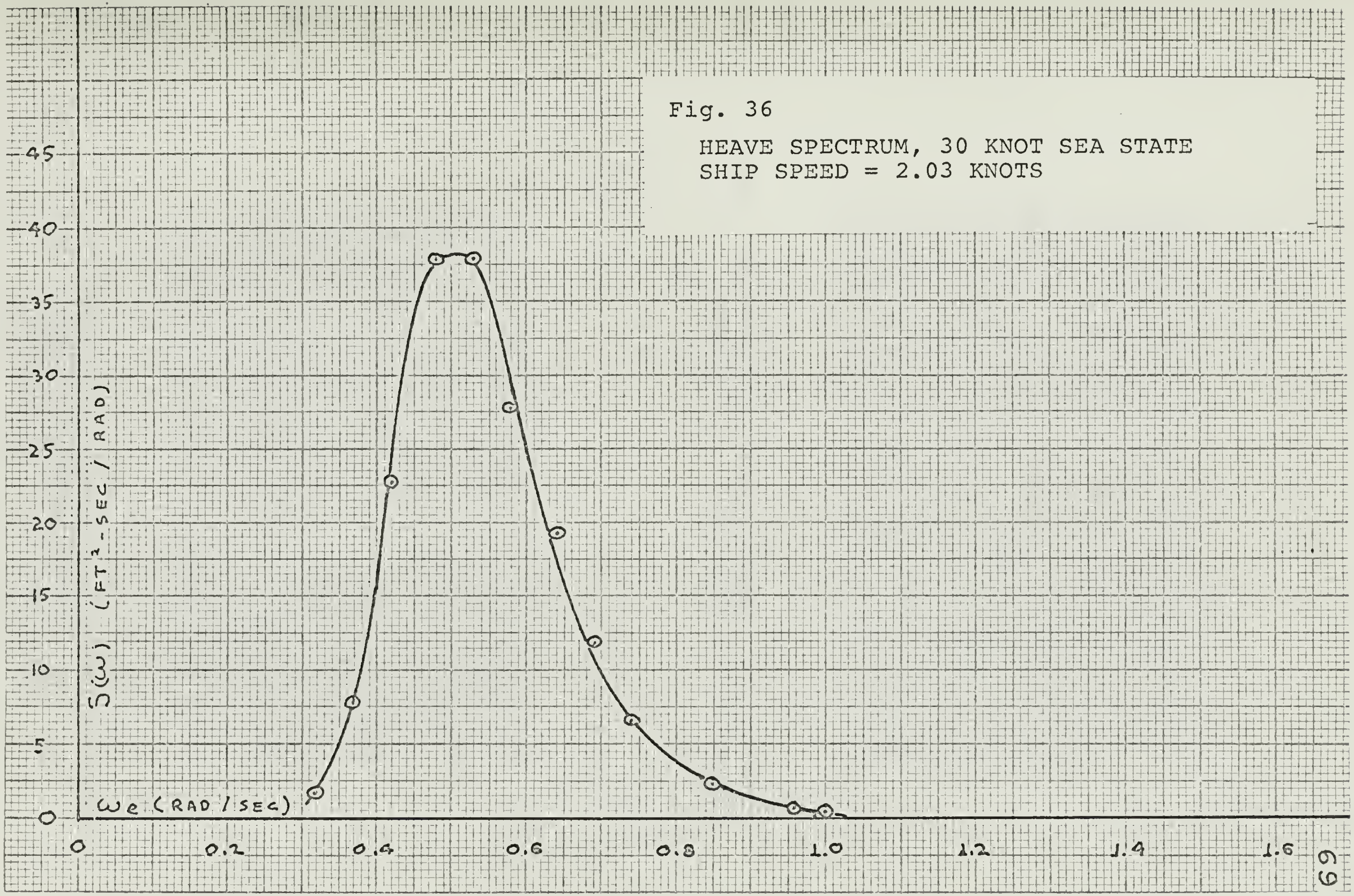



Fig. 35

HEAVE SPECTRUM, 30 KNOT SEA STATE
SHIP SPEED = 0.00 KNOTS

Fig. 36

HEAVE SPECTRUM, 30 KNOT SEA STATE
SHIP SPEED = 2.03 KNOTS



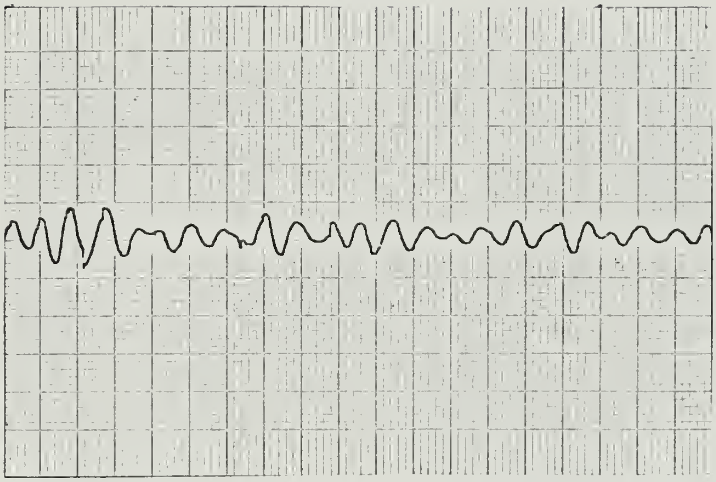


Fig. 37. Vertical Bending Moment in 30 Knot Head Seas. Ship Speed = 2.03 knots.

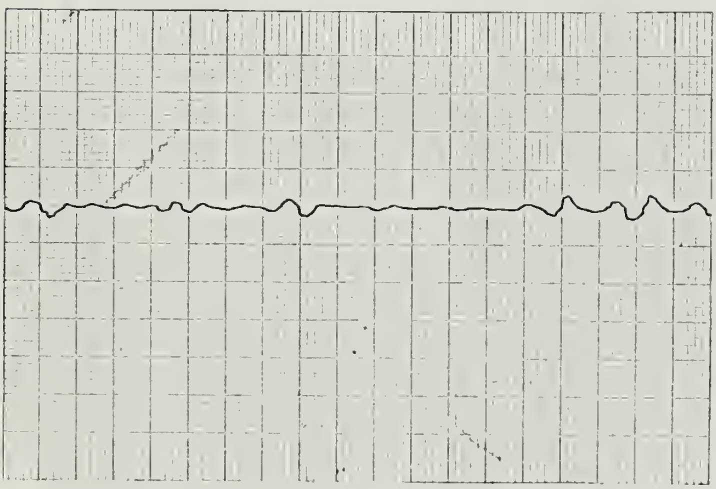


Fig. 38. Vertical Bending Moment in 30 Knot Following Beam Seas. Ship Speed = 2.03 knots.

Thesis
R679 Rogalski 118371
An experimental study of the effect of wind-induced drift on the roll response of a hull in beam seas.